INTERNATIONAL
HELLENIC
UNIVERSITY

Modelling of Solar Thermal Technologies for Desalination

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SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

Master of Science (MSc) in Energy Systems

DECEMBER 2020

THESSALONIKI – GREECE

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Abstract

This dissertation was written as a part of the MSc in Energy Systems, School of Science and Technology, at the International Hellenic University. Water scarcity is a world developing problem of utmost importance. Initially, the subject is a suggestion of technology aiming to address the freshwater need in Greek arid islands. There lies the optional implementation of desalination of the sea or brackish water. Since the scope of desalination facilities subsists, the most important ones are analyzed thoroughly from the technology, economy, and worldwide installation point of view. Among the technologies, the interest lies in the thermal ones. Desalination is very mature but inherently energy-intensive, highly dependent on fossil fuel consumption, resulting in high costs. Indirectly it is exacerbating climate change, one of the most challenging matters nowadays. The proposal in this thesis tackles most of these issues with Concentrated Solar thermal Power. The methodology applied is logical steps, one after another, that examine the desalination facility location, capacity, energy demand, and results in the renewable energy technology to be used. A series of simulations unfold, on the System Advisor Model program, designing, and optimizing the Concentrated Solar Thermal plant. For the selected island of Lipsi, a Multi-Effect Distillation desalination facility, with 230m^3/day freshwater capacity, is covered thermally by a plant of 12.95MWt actual capacity, with Pressurized water heat transfer fluid and thermal storage of 6hours. There is also a short discussion on the high competitiveness with other renewable energy sources or desalination technologies, and environmental impacts that should not be neglected.

Acknowledgments must be given to my supervisor, Prof. Mr. George Martinopoulos. He is an absolute professional and contributed when tirelessly correcting this work, providing his insight, and specialty on this scientific subject. My family, work colleagues, and friends, cannot be neglected to acknowledge while supporting and encouraging me when needed.

Evangelia N. Fotiadou

10-1-2021

Keywords: desalination; concentrated solar power; water scarcity; climate change; Greece

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Abbreviations

Abbreviations	**Explanation**
€	Euros
BC	Before Christ
CA	California
CAPEX	Capital Expenditure
CF	Capacity Factor
CSP	Concentrated solar Power
DIF	Diffuse Horizontal Irradiation
DNI	Direct Normal Irradiance
ED	Electrodialysis
ELE	Terrain Elevation
GHI	Global Horizontal Irradiation
GOR	Gain Output Ratio
GTI_opta	Global Tilted Irradiation Optimum Angle
H2O	Water
HDH	Humidification-Dehumidification
HEX	Heat Exchanger
HTF	Heat Transfer Fluid
KSA	Kingdom of Saudi Arabia
LCOE	Levelized Cost of Electricity
LCOH	Levelized Cost of Heat
LT-MED	Low Temperature Multi-Effect Distillation
MD	Membrane Distillation
ME	Multi-Effect
MED	Multi-Effect Distillation
MED-TVC	Multi-Effect Distillation-Thermal Vapor Compression
MSF	Multi Stage Flash Distillation
NF	Nano Filtration
O&M	Operation and Maintenance
ppm	parts per million
PV	Photovoltaics
RO	Reverse Osmosis
SAM	System Advisor Model
SCA	Solar Collector Assembly
SCM	Solar Collector Module
SIDS	Small Island Developing States
SM	Solar Multiple
SWRO	Sea Water Reverse Osmosis
TDS	Total Dissolved Solids
TEMP	Annual Air Temperature
TES	Thermal Energy Storage
TX	Texas
UAE	United Arab Emirates
US	United States
USA	United States of America
USD	Unites States Dollar
VC	Vapor Compression
WEI	Average water demand-availability ratio
WHO	World Health Organization
WWII	World War II
WWR	Withdrawal to Availlable Water Ratio

1 Introduction

Water scarcity is a complex and growing problem. It stems from overpopulation and local arid climate. Water is valuable for life preservation, and in certain areas on the planet, people hardly access more than 500m^3/capita/year. Freshwater scarcity is also appearing on the Mediterranean Greek arid islands. Greece is generally rich in water thanks to its temperate climate, but a few islands are more remote and dry. There are a few options to tackle this problem, such as water-saving, recycling, and others. But the most usual, is the desalination technologies, mature and tested for many years now and worldwide. Chapter 2 is the Literature Review, where the reader is introduced to water scarcity and desalination. Desalination of the sea or brackish water is the technology of removing the salts and other minerals, leaving as a main product fresh potable water and as byproduct brackish water of high salinity. Continuing with desalination analysis, some of the main methods, Thermal and Membrane are presented. Thermal technologies are Multistage Flash Distillaton and Multi-Effect Distillation. The Membrane technology is Reverse Osmosis. An informative section follows with the worldwide capacity and installations per method, also by quantity, quality, and percentages. The capacity advantage nowadays lies upon the Reverse Osmosis installations worldwide, but it is competing with the high reliability of the Thermal technologies that deliver a better-quality final product. There is a general comparison of these technologies.

The two issues arousing to be tackled are the cost ineffectiveness and fossil fuel dependency. Chapter 3 is referring to them. High costs are the result of complexity. Factors such as energy consumption, particularly coming from fossil fuels, location, plant size and economies of scale, feedwater quality, target product water quality, environmental impacts, and the regulations per country only emphasize the cost ineffectiveness. Desalination is three operations together: pre-treatment of feed water, desalination technology itself, and post-treatment of product desalinated water. These operations contribute differently to each economic factor, usually worsen the problem. Fossil fuel dependency is inevitable in most cases. Most facilities are near energy production facilities that primarily use such fuels. Or the renewable energy sources are unable to implement nearby to use for desalination. The world is, in general, trying to cope with fossil fuel dependency due to climate change lurking and worsening. There are worldwide efforts with the development of renewable energies. Desalination could not be an exception to the solution. Concentrated Solar Power, Photovoltaics, Wind, are the renewable energies combined in many cases with desalination to produce an environmentally friendly freshwater. Greece is not an absent country when it comes to the solution of such problems. There is a wide variety of Reverse Osmosis and thermal desalination facilities, operating mainly with primary energy and secondarily with renewable energy. Greece is a country with medium and small island networks, highly dependent on tourism. The electric power and the freshwater supply are an existing problem for many years now. Like Greece, Small island developing states, like the Maldives, are also coping with these by implementing, and so far, preferring Reverse Osmosis desalination with Photovoltaic or Wind Energy.

A focus on the problem can only emphasize the need for renewable desalination. The importance of fossil fuel dependency and water scarcity is tremendous. On the one hand, humanity would not be able to live without fresh water. Water means life. The rapid development of technology, life expectancy, life quality, unevenly distributed on the planet, has constituted water even more valuable than ever. Water is used everywhere, including industries, leading to severe imbalance of the water cycle. It was unable for desalination not to be developed and applied. With the increasing desalination capacities worldwide, fossil fuel dependency, on the other hand, only worsens. Fossil fuel dependency leads to climate change, which in turn is inevitable and is already happening. The possibilities of making it reversible are to the minimum. And that is where renewable desalination is one suggestion. Greece must be a part of the solution.

The contribution, Chapter 4, is following a methodology comprising of logical steps. Each step examines a parameter and suggests a solution. It is necessary that only if one step is solved one can proceed to the next. These steps are the evaluation of meteorological and local parameters, the seawater characteristics, the capacity of the desalination facility, and island choice. The selected island is Lipsi, in the Dodecanese complex, where a Multi-Effect Distillation desalination facility of 230m^3/day freshwater capacity. The thermal capacity of the line Concentrating Solar facility is determined. After this methodology, the valuable simulation is conducted in the System Advisor Model, a program of the National Renewable Energy Laboratory of the United States of America,. After the first simulation, there is plant optimization to cover the thermal needs during winter and summer. The result summary in Chapter 5 is a Concentrating Solar plant of 12.95MWt actual thermal capacity, with Pressurized water as heat transfer fluid and thermal storage of 6hours. The location on the island is selected. The land area needed is not a disturbance for tourism or the environment, as also seen in Chapter 5.

This approach is innovative because there are not many facilities of concentrated solar thermal desalination of that scale. Chapter 6 is a short discussion on this approach under a prism of competition and environmental protection, The existing facilities are successful, despite being few in numbers. There is quite a competition with both Reverse Osmosis and other renewable sources such as wind and photovoltaics. The same is not only for Greek islands but other similar small island developing states as well. Environmental issues that may occur from such a facility, and exact location, under the Hellenic state law and European regulation, is certainly not to be neglected in the possibility of realization of such a facility.

Conclusions are in Chapter 7. The suggested technology is a novelty in Greece, can be altered for any other arid island or location and scale. The ample direct normal irradiance of Greece should not be unexploited, and there should be an approach different from the usual renewable energy sources. Additional research for the solar thermal field design and economic viability is necessary.

2 Desalination Technologies Literature review

Water means life. But water is not always fresh and especially on our planet of seven (7) billion people. Freshwater is even more valuable and can be complex to reproduce since only 3% of earth's water is sweet, and out of it only 1% can exploit or drink [1]. The term "water scarcity" stems from the unprecedented population growth relative to the available water resources that cannot keep up with the growing demand (physical water scarcity). Often enough, the luck of water management and infrastructure add-up to the problem (economical water scarcity) [2]. About half of the world's population has access to less 500m^3/capita/year, while the accessibility for the rest of the usually more developed world is more than 1000m^3/capita/year. In general, the higher the population density, the higher the unavailability of freshwater. The below figure shows the spatial distribution of available freshwater in m^3/capita/year, followed by another depicting the spatial distribution of water stress represented by withdrawal-to-available water ratio(WWR), indicating in any case that the fundamental drivers of water stress are supply and demand [2].

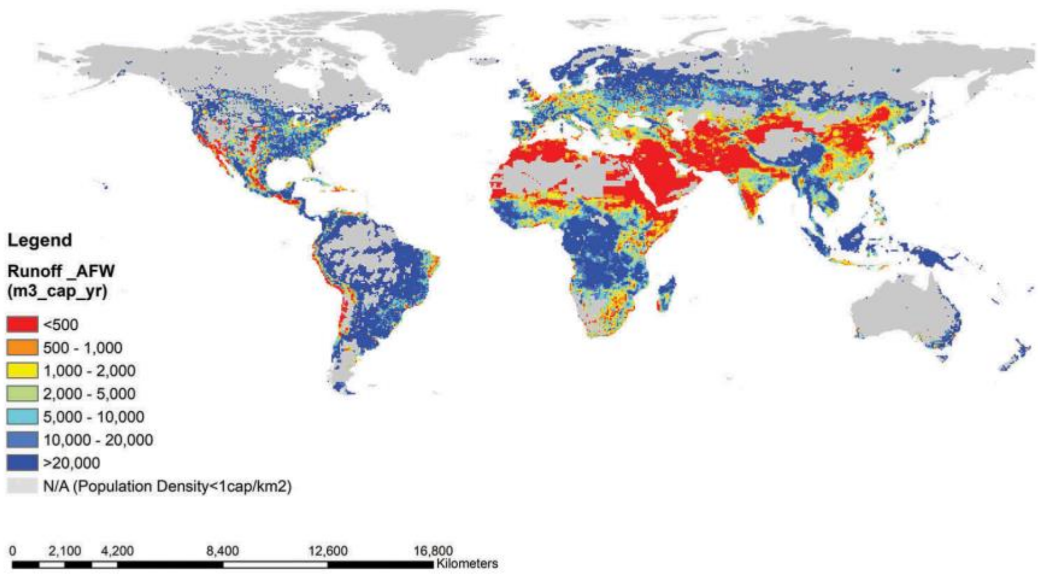


Figure 1: Spatial distribution of available freshwater (m^3/capita/year) [2]

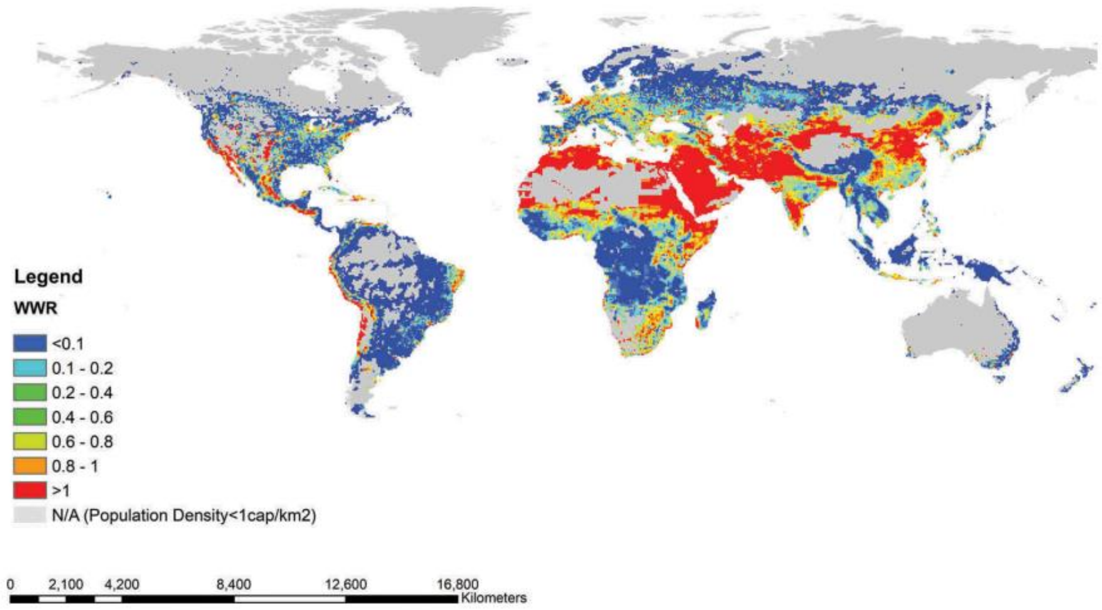


Figure 2: Spatial distribution of water stress represented by withdrawal-to-available-water ratio (WWR) [2]

Freshwater scarcity is both social and economic problem for the countries that suffer the most. As for all sources, freshwater can also be used more efficiently from all sectors of agriculture, industry, municipal waste, and human needs in all countries. Policies can be incentivizing the most consuming sectors of industry and agriculture. But even household consumption in large cities that are fast urbanizing can have a significant contribution to reducing water scarcity. Studies of the USA, Australia, and United Kingdom resulted that when installing water-saving devices in households, the efficiency of those was from 9 to 12%, and combined with other highly water-efficient appliances, the water saving could reach up to 50% [3]. But the main problem in developing counties and countries that are near the equator remains. Even though a few nations have implemented policy, with great success, worldwide improvement in agriculture was approximately 1% per year for agriculture and 1% for industry [4].

The available solutions to water scarcity are wastewater and drainage reuse, and desalination. Depending on each country's location and economy, desalination technology is the most promising solution. Desalination is the process during which brackish or sea saline water is turned into freshwater and so salts are removed from the original feed. The products of this process are freshwater and saline solution (brine).

So, since the previous century, people enhanced this technology that gave a solution to cover the high freshwater demand. Desalination is known for centuries, as far back as the 4th century BC since Ancient Greeks were producing fresh water by evaporation, to cover their needs of freshwater during long nautical journeys [5]. Up to 18th and 19th century people where desalinating water for the same purpose of covering the needs of the Navy. But in industrial scale the first country to build and use a desalination plant was Egypt in 1912 [6]. In general, the Arabian Gulf countries where the first to hire a Dutch company to install two distilleries called by the local people “Kendassa” or in English “condenser”. In 1928, King Abdulaziz Al Saud ordered to replace them by two new units using submerged tube process of a total capacity of 135 m^3 /day installed by the Scottish Westgarth Weir company [4],[7]. Like every technology used today, desalination was the object of rapid growth during World War II, when there was an excessive need for potable water from military groups in arid areas. After WWII there was an extensive research on the field and so by late 1960’s commercial desalination units where producing 8000m^3/day [8].

Nowadays, the need to use technologies that are less dependable from fossil fuels and more sustainable and affordable is also increasing. Therefore, desalination is one of the most opportune technologies where the world is focusing on. What needs to be highlighted is that it is not only the technology itself that matters and contributes to the optimization of all these factors, but the quality of water to be treated and the science behind, like how much energy must be consumed, are factors that can hardly change. What can change, when possible according to location, is the energy source.

2.1 Desalination technologies

All desalination plants are composed of three basic operations: pre-treatment of source water, desalination, and post-treatment [9],[10]**.** Source water according to its location, will be analyzed in the following paragraph and plays a major role in the choice of technology and the final product use as well. In addition to that, the second operation diversification is also affecting the first and third ones and is the heart of the plant. The following figure shows the basic operations that every desalination plant consists of [11]:

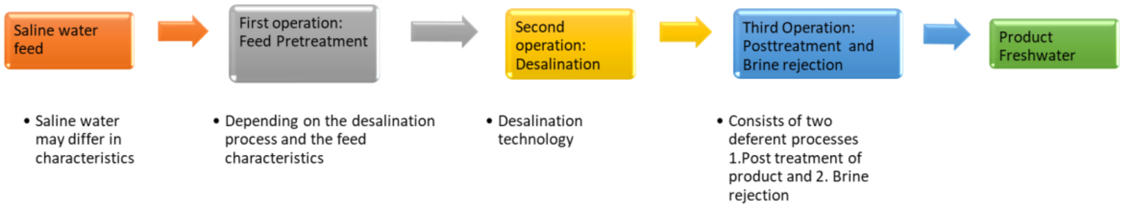


Figure 3: Operations that every desalination plant consists of [11]

Desalination technologies are classified mostly according to separation method, generally meaning whether the feed goes through phase change or not [9].

Separation method classification: Thermal Evaporation, Membrane, Other [9]

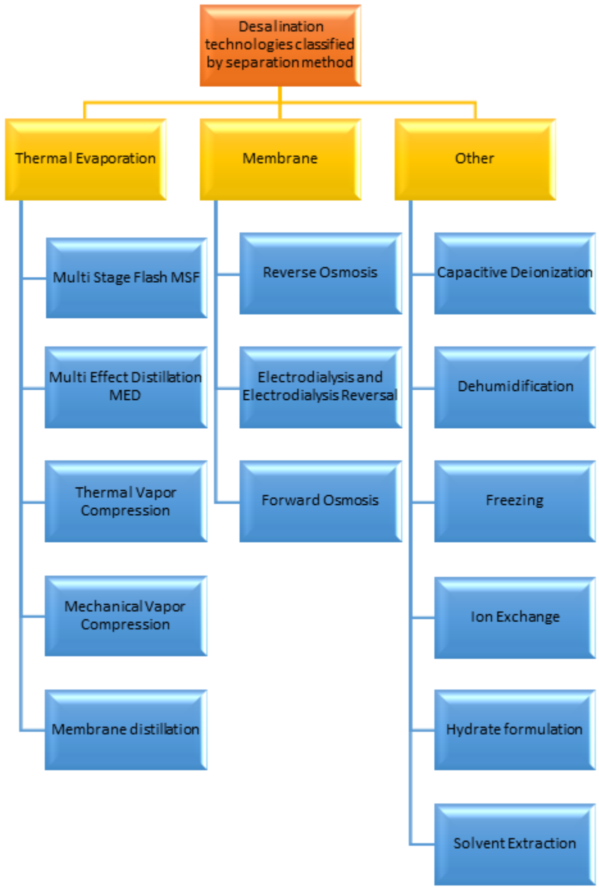


Figure 4: Desalination technologies classified by separation method [9]

In this essay the focus is going to be in the most usual technologies worldwide, Multi-Stage Flash (MSF) and Multi-Effect Distillation (MED) of the Thermal Evaporation ones and Reverse osmosis of the Membrane ones that gains ground the last years. Other technologies like Electrodialysis (ED), Nanofiltration (NF), Humidification-Dehumidification (HDH) will not be of concern.

2.1.1 Thermal Evaporation Technologies

An explanation of the thermal processes is the following:

In the category of thermal processes the feed-water is changing phase either by crystallization or distillation [1]. Since crystallization is rarely the chosen way of phase change, the main logic is that there must be a distillation of the saline water. The water is heated to produce vapor and in turn condenses to form the final product freshwater. But in industrial scale, the adjustment of atmospheric pressure and boiling point is controlled. So, to achieve this there are needed multiple stages and scale control [11]. To fully understand the Multiple stages of thermal processes, the following theory can be of use.

Boiling water is a process of stages dependent on temperature and pressure. When temperature equals 100^{o}C in atmospheric pressure water starts to vapor and boil. The energy given to the water in the form of heat is the heat of vaporization.

1. The first stage of a multiple-stage desalination plant is the boiler where the feed saline water is heated to the boiling point via heat transfer. The heat is produced with steam.
2. The heat is turned off, boiling occurs by reducing the pressure instead of adding more heat in a compression chamber. The extra heat needed is achieved because the temperature increases since the conditions are not atmospheric, and boiling is continuous. When the heat equals the one of vaporization in specific pressure and temperature conditions, then the saline water rapidly evaporates or using the proper term, flashes. During this process, which is called stage-flash, only a small percentage of this water vapors. Stage-flash is repeated with different pressure changes each time and so this second step of successive compression chambers is the multiple stage flash. So, the brine is passing through the chambers and releases the heat that was exchanged in the first stage until it reaches the extreme point of water boiling and freezing simultaneously. In that way, both brine and product water exit the plant at the lowest temperature possible.
3. Heat is recovered by recirculation of the brine while mixed with seawater and passes through the top flash stages in heat exchangers. This recirculation stage may not exist, and the plant is a once-through one. In that case, the efficiency is reduced because there is no seawater preheating and tubes are less corroded because brine is de-aerated, and condensates released are even less [11].

A typical flow diagram is the following:

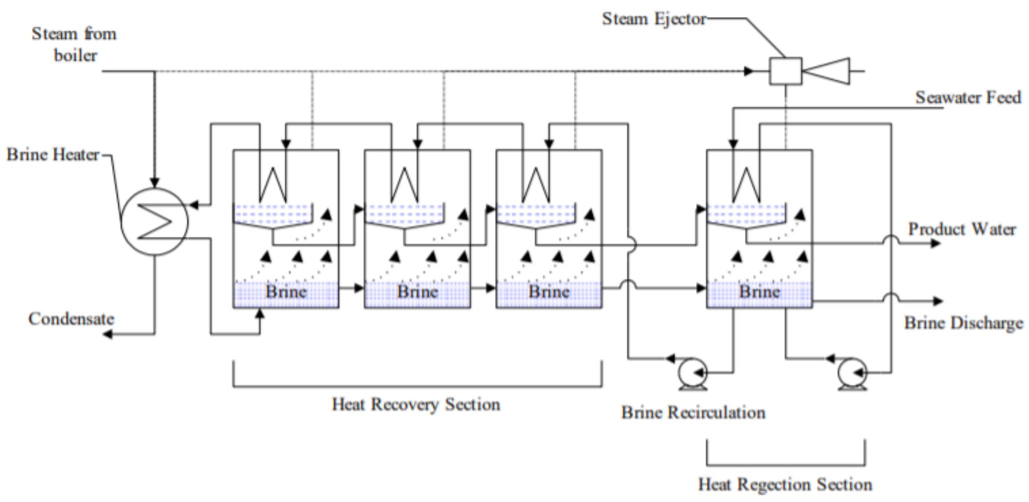


Figure 5: Multi Stage Flash Thermal desalination technology in flow diagramm [4]

The performance ratio is the mass of distillate produced divided with the one of steam consumed. The upper limit for Multiple-stage flash is practically 12 [11].

Another method of multiple stages is Multi-Effect Distillation MED comparted by the following:

1. Hot steam is produced in a boiler and is going to be used in a heat exchanging bundle.
2. A bundle contains, on the one hand, a heat exchanger where hot steam releases its heat and tubes onto which spraying saline water occurs. On the inside part of the bundle, the saline water evaporates to produce vapor and brine, while on the outside, the phenomenon is steam condensation, and the product is desalinated water. This vapor needs treatment, as it contains salts, and after this, it enters the inside of tubes of the heat exchanger of the next bundle. This process is one "effect" distillation, while the next ones occur in lower pressure.

This process can happen for up to twenty effects, with the lowest number of them being five. The advantage of this procedure is that heat is needed only in the beginning, while the more the effects, the higher the internal energy recovery [9]. The variants though that can diversify one MED plant from another are Multi-Effect submerge tube, Vertical tube climbing-film, and Vertical or Horizontal tube falling-film. But the main factor that can have a significance on cost is performance ratio and thermal energy consumption [11]. One typical flow diagram of this technology is the following:

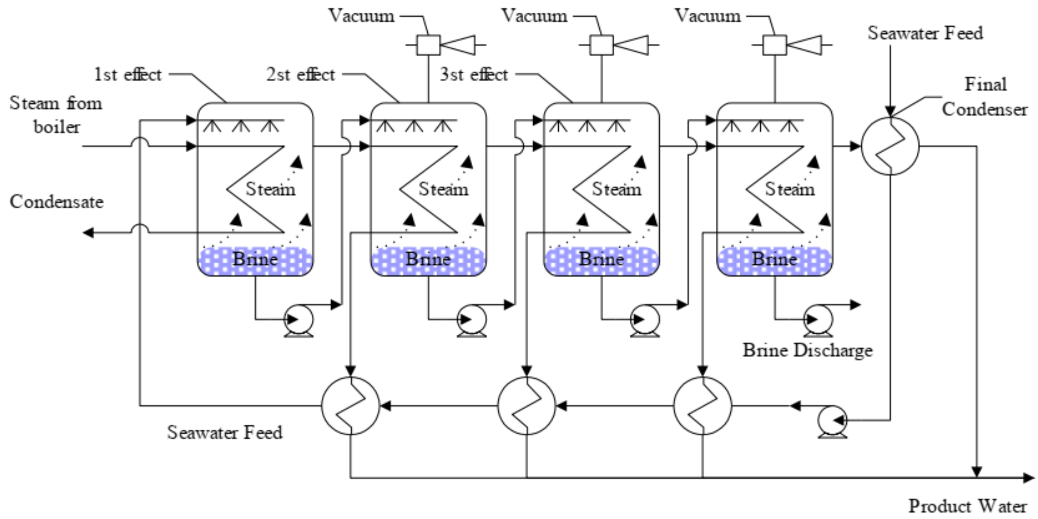


Figure 6: Multi Effect Distillation Thermal desalination technology in flow diagramm [4]

2.1.2 Membrane Technologies

Membrane technologies are the separation of water from salts with the use of semipermeable membranes. No phase change occurs. In Reverse Osmosis technology, compression or osmotic pressure is the key to make the high salt concentration aqueous solution seep through a membrane. On the other side of the membrane, the lower salt concentration water solution separates. Both solutions are in balance with each other, and equilibrium occurs. It also occurs because there is a concentration gradient between the solutions. The natural flow would be from low concentration water to high concentration salt solution, and because this flow is reversed with the external pressure application therefore the technology is reverse osmosis [1],[9]. In conclusion, no heating or phase change is necessary. The more energy needed is for the pressure, by pumping the saline feed water into a closed vessel. The remaining feed water that does not pass the membrane after equilibrium is achieved has to be discharged to avoid precipitation of supersaturated salts and increased pressure. This remaining water is about 20 to 70 percent of the feed flow and depends on the original feed salinity [11]. The main difference between Reverse Osmosis and other technologies is that it is not simple filtration. It occurs at the molecular level, meaning that it is not a physical process but a chemical interaction and diffusion of water across the membrane. So, the pre-treatment of water feed has high standards, is an absolute necessity in the process, and consists of clarification, chlorination and dichlorination, antiscalant dosing, and biocide dosing. The treated feed passes through the high-pressure pump with pressure ranges from 17 to 27 bar for brackish water and 54 to 80bar for seawater. The next step is the membrane assembly, which is a pressure vessel, and the membrane that permits the feed water to pressure against it. No membrane is perfect enough to both withstand the pressure and completely filtrate the feed water. The resulting water still contains salts. Simultaneously the remaining brine emerges from the membrane modules at high pressure so containing energy that is recoverable from 20% up to 40% in large plants in turbines. Cost, feedwater quality, and product water capacity are the main factors for membrane choice.

There are many types of membranes: tubular modules, plate and frame modules, spiral wound, and hollow fiber modules [12]. They are typically cylindrical to spread the pressure on the whole surface and achieve equilibrium. The number of membranes installed in parallel can affect the performance ratio of the process. Typical characteristics of the reverse osmosis membranes are:

1. They consist of a thin polymer film of some thousand Angstroms thickness installed in porous polymer,
2. Commercial membranes are highly water permeable and high impermeability resulting in the fraction of water flow to the flow of dissolved ions being very high,
3. They must have fixed performance in a wide temperature range and pH, but also good mechanical strength,
4. Commercial membranes have a lifespan of 3-5 years depending on the membrane, quality of feed water, and plant function, and
5. Most of them consist of cellulose acetate and polyamide.

The more used membranes are the spiral and the hollow fiber ones shown schematically below:

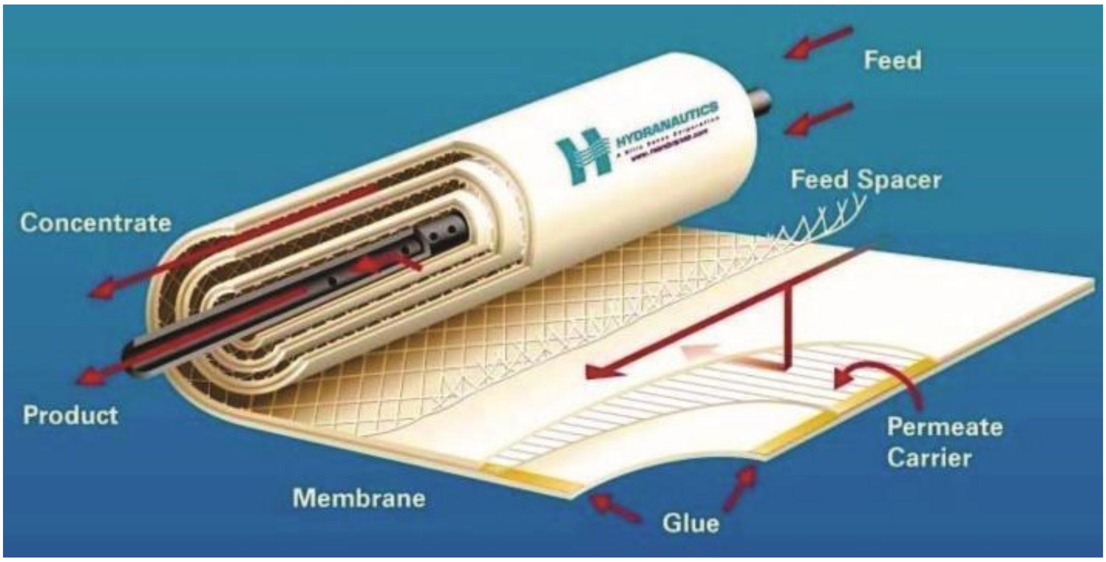


Figure 7 : Scheme of Spiral wound membrane used in reverse osmosis desalination [13]

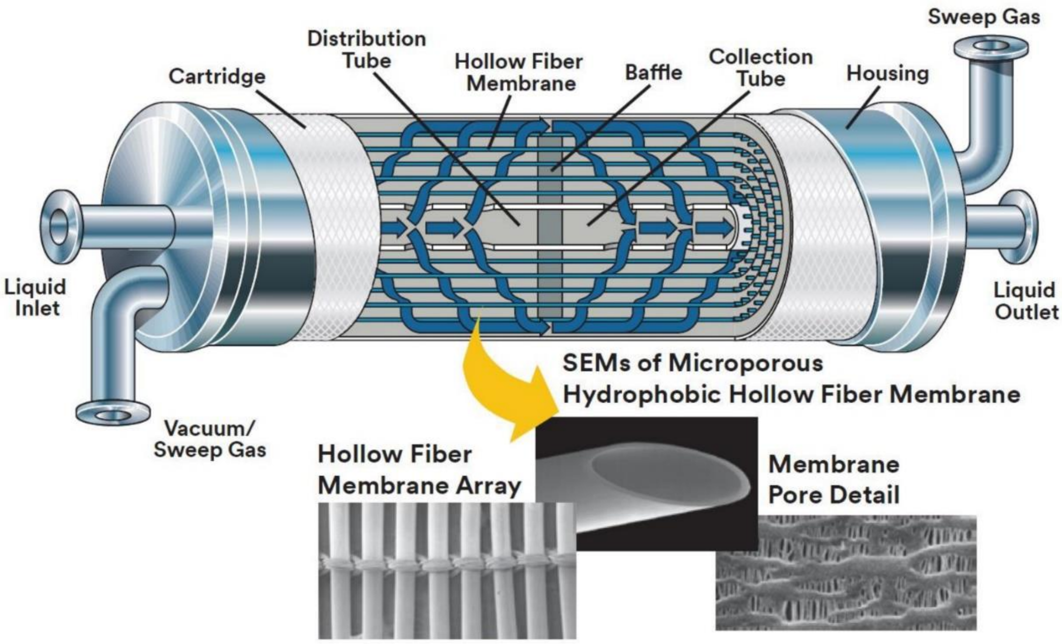


Figure 8 : Scheme of Hollow Fiber Membrane used in reverse osmosis technology [14]

Post-treatment of the product is also more than necessary to apply [9],[11]. A typical flow diagram of a Reverse Osmosis plant is the following [4]:

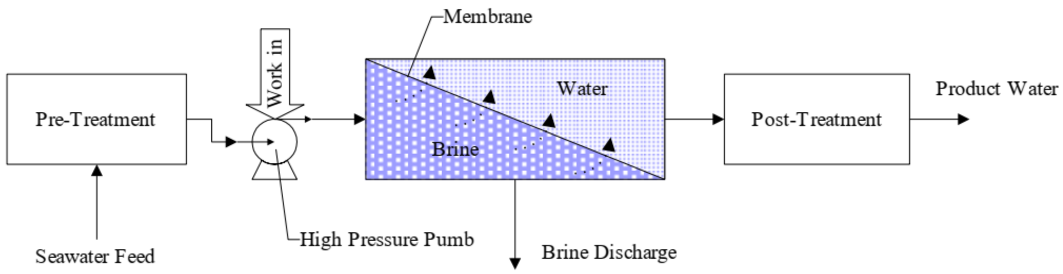


Figure 9: Reverse Osmosis Membrane desalination technology in flow diagramm [4]

2.1.3 Solar thermal technologies coupling

According to several studies, in the near future it will be more likely that access to water will be much more difficult than to fossil fuels [15]. Simultaneously, the sustainability of resources like energy and water is disrupted in general and the need to be less dependent to fossil fuels is imperative. Even in the areas that have easy access to fossil fuels to desalinate water, the processes are operationally expensive and polluting. Especially in coastal areas that have access to seawater, fossil fuels for energy production are not an option due to high costs. So, renewable energies are very much desirable [15]. Solar and Wind energies have the highest share of all types of renewable ones to provide electric power, mainly because the desalination facility is in areas where these sources are abundant. Other methods such as biomass, hydroelectric power, geothermal, and ocean energy are usually implemented in smaller capacity plants [15]. In the present paragraph for the needs of this thesis there will be no reference in other renewable energies, apart from Solar Thermal ones.

Solar power is used either directly or indirectly for desalination purposes. Collection systems that produce distillate directly in the solar collector are solar ponds, and solar Hydration-Dehydration, but that field is beyond the scope of this thesis and not to be analyzed further. Solar energy is used indirectly with concentrated solar power or concentrated photovoltaics. Sunlight is reflected and focused on a receiver to be transformed into thermal energy, which in turn is used in a heat exchanger to produce steam. Steam is in turn either used in desalination or as well in a turbine to produce electricity in a generator [16] The desalination technologies then coupled with solar thermal ones are:

- those that need thermal energy, so steam, but also electricity, such as Multi-Effect Distillation (MED), Multi-Stage Flash(MSF), Thermal Vapor Compression (TVC), and Membrane Distillation (MD),

- those who need only electricity, such as Reverse Osmosis (RO).

The following figure depicts the solar energy coupled indirectly with desalination technologies:

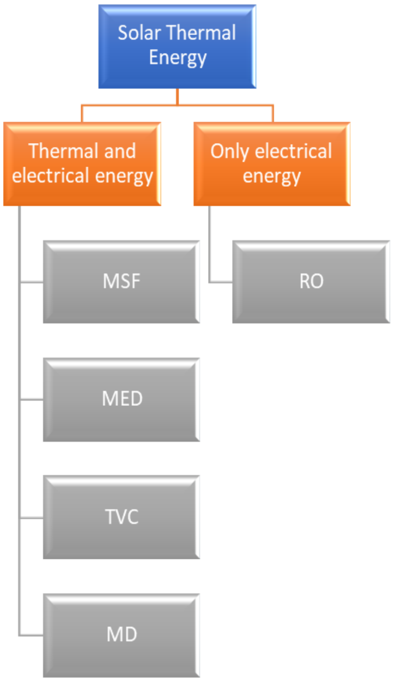


Figure 10: Solar Thermal Energy coupled with Desalination Technologies [16]

Solar collectors used for desalination are divided into two categories based on the temperature [15]:

1. Medium-temperature solar collectors, including flat-plate and vacuum tube collectors, that produce temperatures up to 430°C. Heat transfer is achieved either with water or air and is supplied indirectly with a heat exchanger.
2. High temperature Concentrated solar power collectors, including parabolic trough collectors, central receivers, Fresnel collectors, solar towers, and Stirling dish systems, for temperatures up to 1000°C. For these systems it is optimum to use trackers to achieve the highest efficiency. The parabolic trough and Linear Fresnel are Line Concentrators, while the Solar towers and Stirling dish are Point concentrators, depending on where the concentration is done, where it is focused. The concentration ratio of parabolic trough and linear Fresnel is suitable for producing heat for desalination while power generation, as well as for solar towers, ranges from 5 to 200MW with an efficiency of 30 to 40%. Stirling dish produces up to 10kW with an efficiency no more than 15%. A schematic representation of each technology is shown in the below figure:

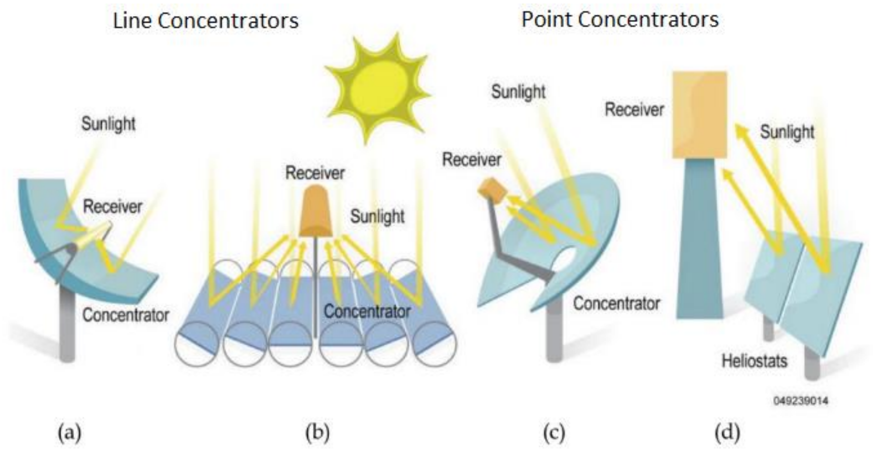


Figure 11: Solar concentrating systems a)parabolic trough, b)Fresnel collector, c)Stirling dish collector, d)Solar tower [17]

Because MED compared to MSF requires lower steam of temperature and pressure, it is ideally combined with concentrated solar systems. For example, La Desirade Island in the Caribbean has installed an MED desalination unit of 14 evaporation stages combined with a low-temperature solar site, producing 40m^3/day fresh water [15]. The following figure depicts a typical parabolic trough configuration. The stage 1 consists of the parabolic troughs that heat a specific oil or Heat Transfer Fluid closed loop. The stage 2 is another closed steam loop where the steam is superheated at around 380^{o}C and is sufficient to produce electricity in a non-condensing turbine and then used for desalination in an MED plant (stage3). The temperature of steam for desalination is 135^{o}C and after stage 3 is de-aerated and preheated to superheat again for power production [17].

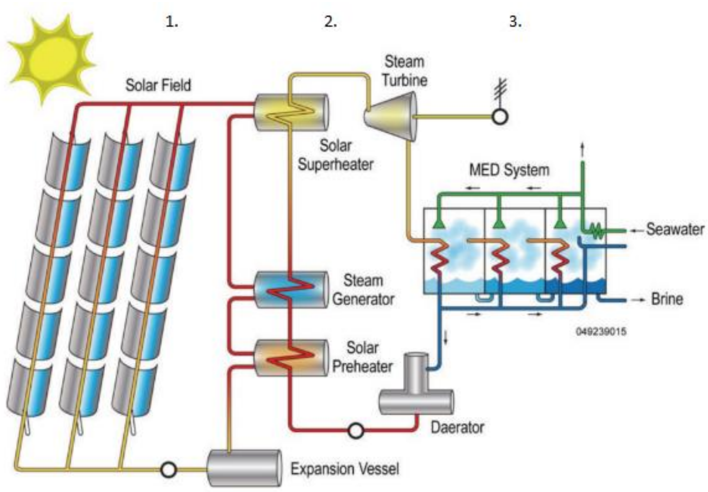


Figure 12: Parabolic trough power plant with oil steam generator and MED desalination [17]

Worldwide renewable desalination is blooming, with more than 130 plants being installed the past years and Concentrating solar power being the most promising technology [18]. Being more precise, the solar thermal desalination plants in the world are summarized in the following table [19]:

Table 1: Summary of solar thermal desalination plants in the world [19]

Project	Capacity(m^3/day)	Process
Margarita de Savoya, Italy	50-60	MSF
Islands of Cape Verde	300	Atlantis Autoflash
Tunisia	0.2	MSF
El Paso, Texas, USA	19	MSF
University of Ancona, Italy	30	MEB
Dead Sea, Jordan	3000	MEB
Safat, Kuwait	10	MSF
Takami Island, Japan	16	ME-16 effects
Abu Dhabi, UAE	120	ME-18 effects
Al-Ain, UAE	500	ME-55 effects, MSF-75 stages
Arabian Gulf	6000	MEB
Al Azhar University, Palestine	0.2	MSF 4stages
Almeria, Spain	72	MED-TVC 14 effects
Berken, Germany	10	MSF
Hzag, Tunisia	0.1-0.35	Distillation
Gran Canaria, Spain	10	MSF
La Desired Island, France	40	ME-14 effects
Lampedusa Island, Italy	0.3	MSF
Kuwait	100	MSF
La Paz, Mexico	10	MSF 10-stages

But in general Solar thermal desalination with MED or MSF are only 22% of global renewable desalination as RO becomes more competitive, as shown below [16]:

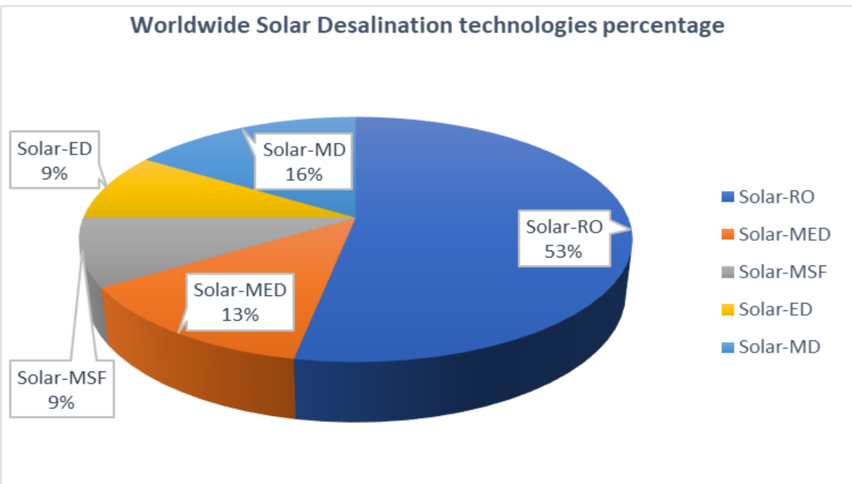


Figure 13: Worldwide Solar desalination technologies percentage [16]

2.1.4 Desalination Technologies comparison

Technologies are differentiated and chosen according to basic criteria such as product water quantity and quality, location, feed water temperature, availability of cheap energy and hybrid plants possibility, waste brine disposal, and process economics. From these criteria the resulting factors are energy consumption, scale economy, maintenance, feed pre-treatment and salinity, post treatment and brine rejection and finally lifetime expectancy. Technology choice for Greek arid islands is going to be analyzed in a different paragraph.

The summary of all data needed is given in the following table for the three most popular technologies analyzed above [12],[20],[21]:

Table 2: Basic Energy data of MSF, MED and RO technologies [12],[20],[21]

Process	**Primary Energy**	**Maintenance requirements**	**Exergy of Steam (kWh/m^3)**	**Electric Energy Equivalent (kWh/m^3)**	**Product Water Quality (ppm TDS)**	**Max plant capacities (m3/d)**	**Total Energy Consumption (kWh/m^3)**	
							min	max
MSF	Steam	Low	7.5-11	10-14.5	~10	5000-60000	65	635
MED	Steam	Low	4-7	6- 9	~10	500-20000	60	172
SWRO	Electricity	High		4- 6 with energy recovery 7- 13 without it	~350-500	128000	12	24

The main advantages of thermal processes are:

- the suitability of processing sea water because salts' content does not affect the process,
- high reliability since it is a tested technology through the years,
- minimal pre-treatment requirements,
- exploitation of low-enthalpy waste heat from power plants and if coupled with a cheap heat source can be economically effective,
- high product quality

On the other hand, it is highly dependent of feed and operating temperature it is very likely to create tube scaling, mostly of calcium sulfate ($CaSO_4$) because of high temperatures leading to an upper limit of 120°C of brine and thus lower efficiency. But the least wanted characteristic is the high energy consumption due to temperatures and Gain to Output Ratio (GOR) [20].

Reverse Osmosis technology has the following very important advantages:

- consumes relatively less energy,
- is smaller and more compact if needed, and
- can be of lower investment cost.

On the other hand, the membrane characteristics such as thermal stability limit, sensitivity to fouling can be very binding as well as creating high dependency and costs on pre-treatment, low life expectancy, high maintenance requirements and operating costs. Finally, product is not as high quality as in thermal processes [20].

The following table summarizes all advantages and disadvantages of the most critical processes [21].

Table 3: Advantages and disadvantages of MSF, MED and RO desalination technologies [21]

Process	Advantages	Disadvantages
RO	Low Energy Consumption	High costs due to chemicals and membrane replacement
	Lower Investment Costs	Dependent on feed quality
	No need for cooling water	Pre-treatment has high standards and is necessary
	Simple Function and immediate initiation	High sensitivity of membranes to bio-sediments
	High production per surface	Susceptible to mechanical failures due to high pressures
	Simultaneous removal of infectious agents apart from salts	Need for high trained stuff
	Maintenance without shutting the unit	Low lifetime of membranes 5-7 years
MED	Minimum pre-treatment feed requirements	High energy consumption
	High credibility and minimum working stuff	High investment and operating costs
	Sufficient levels of dissolved and organic materials	High demand of high-quality materials since the process is sensitive to corrosion
	High quality of product water	Demand of cooling and stirring of product material before used as potable
MSF	High capacity plants	High capital investment
	Highly reliable and tested technology with great lifetime	Energy intensive process
	Low scaling	High environmental footprint
	High quality of product water	Susceptible to corrosion because of low quality maintenance materials
	Minimum pre-treatment feed requirements	Shutting of the whole unit for maintenance reasons
	Low dependence on feed salinity	Need for highly trained stuff

2.2 Water and desalination

Desalination is a treatment procedure that aims to remove salt and other minerals, if needed, from a saline solution, usually water. In most cases, saltwater must be converted into freshwater which is valuable for drinking and irrigation. This sub-chapter is going to explain the saline water characteristics used as a feed in the desalination process as well as the product water and what characteristics should it have to be potable. All these factors are important in the desalination technology choice.

Salinity is the first factor to be considered. Saline water is a solution of water (H_2O) inorganic salts and small amounts of organic matter. The latter two are the total dissolved solids TDSs and are the basic byproduct of the evaporation of saline solution water. The principal constituents are usually calcium, magnesium, sodium, and potassium cations and carbonate, hydrogen carbonate, chloride, sulfate, and nitrate anions [22]. Classification of saline water as well as salinity in world waters are shown in the following tables:

Table 4: Water classification according to salinity [9]

Classification according to salinity	TDS concentration (mg/L)
Fresh water	<1000
Brackish water	1000-10000
Highly salty Brackish water	10000-30000
Seawater	>30000

Table 5: Salinity worldwide (mg/lt) [23]

Water location	Salinity TDS (mg/lt)
Red Sea	42000-46000
Persian Gulf	40000-44000
Mediterranean Sea	36000-39000
Caribbean Sea	34000-38000
Indian Ocean	33000-37000
Pacific Ocean	33000-36000
Atlantic Ocean	33000-36000
Baltic Sea	6000-18000
Caspian Sea	12000
Dead Sea	350000-370000

The more saline the water feed, the more the energy necessity increases. Technology preference is changing accordingly.

The second factor to be considered is the safety of source water. Apart from the naturally occurring substances that must be removed in sufficient concentrations for the product freshwater to be potable, pathogenic viruses, bacteria, parasites, and chemical contaminants from human activities, such as petroleum extraction, may be present in the saline source water. Boron (borate), bromide, iodide, sodium, and potassium are chemicals that may require additional actions for removal or are present in such concentrations as to leave significant residues. Naturally occurring chemicals may affect the taste and odor of the final product water, especially when the source is brackish water. Chemicals include non-organic materials, such as humic and fulvic acids, and the by-products of algal and seaweed growth, where this growth occurs to a significant extent, and a range of toxins from a variety of different organisms. Only one of these potential contaminants, the cyanotoxin microcystin-LR, which arises from freshwater cyanobacterial blooms, has a World Health Organization guideline value (provisional) of 1 μg/l [24]. The concentration of the major elements of seawater is presented bellow [25]:

Table 6: Major elements of seawater [25]

Element	**Concentration (mg/l)**
Oxygen	857000
Hydrogen	108000
Chloride	19000
Sodium	10500
Magnesium	1350
Sulfur	885
Calcium	400
Potassium	380
Bromide	65
Carbon	28
Strontium	8.1
Boron	4.6
Silicon	3
Fluoride	1.3
Argon	0.6
Nitrogen	0.5
Lithium	0.18
Rubidium	0.12
Phosphorus	0.07
Iodine	0.06
Barium	0.03

The relevant ionic composition of seawater in the world, including the Eastern Mediterranean is shown in the following table [25]:

Table 7: Ionic composition of seawater (mg/l) [25]

Constituent	Usual Seawater	Eastern Mediterranean	Arabian Gulf	Red Sea
Chloride ($C1^{-1}$)	18,980	21,200	23,000	22,219
Sodium (Na^{+1})	10,556	11,800	15,850	14,255
Sulfate (SO_4^{-2})	2,649	2,950	3,200	3,078
Magnesium(Mg^{+2})	1,262	1,403	1,765	742
Calcium (Ca^{+2})	400	423	500	225
Potassium (K^{+1})	380	463	460	210
Bicarbonate(HCO_3^{-1})	140	--	142	146
Strontium (Sr^{-2})	13	--	--	--
Bromide (Br^{-1})	65	155	80	72
Boric Acid(H_3BO_3)	26	72	--	--
Fluoride (F^{-1})	1	--	--	--
Silicate (SiO_3^{-2})	1	--	1.5	--
Iodide (I^{-1})	<1	2	--	--
Other	1	--	--	--
Total Dissolved Solids (mg/l)	34,483	38,468	45,000	41,000

These factors are of primary significance in the desalination process. Pre- and Post-Treatment can vary according to source water and chosen technology.

- Pretreatment aims to protect the desalination process, but it will also remove hazards present in brackish or saline waters. Residual disinfection stage may not be required because during the desalination process, there is also high effectiveness in removing both microorganisms and chemical constituents. Desalinated water has a significantly low total organic carbon content and low disinfectant demand, so disinfection by-products are generally of little concern, although brominated organics may occur owing to the presence of bromide in seawater. Generally, the removal of higher molecular weight organic chemicals and virtually all inorganic chemicals happen during desalination. Thermal desalination processes are prevailing against membrane ones because the volatile organic compounds are vented. On the other hand, it is important to improve the membrane capability in excluding boron and some smaller molecular weight organic substances from the product water [26].

- The after-desalination water contains lower than usual concentrations of dissolved solids and essential elements such as calcium and magnesium. These elements should be a daily intake in one's diet. But drinking water typically contributes a small proportion for that purpose so that food acts as a supplier to balance the difference. Nevertheless, the product must be stabilized or re-mineralized before distribution. Another reason is that it is aggressive towards materials used for distribution pipes, storage, and plumbing. Distillation processes water contains around 20 ppm TDS while membrane one is of 100-500 ppm TDS. So, post-treatment in essential to reduce its corrosive nature. Stabilization happens when chemical constituents such as calcium and magnesium carbonate are added to the product, along with pH adjustment or when blending with small volumes of mineral-rich waters. The latter blending technique increases the risk of formation of bromate in the distributed water. So, to ensure microbial safety, even the blend needs pre-treatment, because the post-desalination residual disinfectant level may be insufficient to control pathogens present in the blending water. As a result, post-treatment may be very confusing and complex [25],[26].

The World Health Organization (WHO) limits of potable water that are the general guideline are presented below [11]:

Table 8: World Health Organization Standards for potable water [11]

Constitutes	**Concentration(ppm)**	
	Limited values	Max allowed values
Total Dissolved Salts (TDS)	500	1500
Cl	200	600
SO_4^{2+}	200	400
Ca^{2+}	75	100
Mg^{2+}	30	150
F^-	0.7	1.7
NO^{3-}	<50	100
Cu^{2+}	0.05	1.5
Fe^{3+}	0.1	1
NaCl	250	-
ph	7-8	6.5-9

2.3 Desalination in Greece

Greece is the country of Europe with longest coastline of about 14000km. The total number of islands is 2500 but only the 117 are inhabited and only 79 of them have a population of more than 100 people [27],[28]. The country's climate is Mediterranean with low precipitation, dry summers, and wet winters. But precipitation varies along the country since in the west it is higher than in the Aegean, Attica, and Thessaloniki [29]. The most need for water though is also in Thessaly and Eastern Continental Greece due to high irrigation demand. In all Greece and especially in the islands during summer potable water is valuable because of tourism [5]. Storage, surface, and groundwater are not of good quality or quantity to count on. Geological formations of some islands make it impossible to take advantage of the groundwater if any exists. The old distribution networks suffer from leakages, aquifers are over-pumped and integrated water systems are absent in most of the islands.

There are several choices to cover this demand. The first is water transfer from the mainland at high cost. The second is traditional such as dams and boreholes and last but not least is the desalination of sea or brackish water [27]. In the recent government plan for decarbonization of the country until 2028 desalination is amongst the measures to tackle water shortage. It includes the promotion of renewable energy systems coupled with small autonomous desalination units to meet the requirements of about 114 remote island areas. In fact, small wind turbines and or photovoltaics are going to be installed along with Reverse Osmosis units, as well as for larger thermal units the possibility of using geothermal energy or solar thermal systems are quite high. To increase the operating hours of the plants it is an absolute necessity to store energy. Desalination plants are going to contribute to local economic development, less use of bottled water and therefore less environmental pollution, less operation of local electricity production units that are fossil fuel dependent and therefore less greenhouse gas emissions [30].

The following table shows the water abstraction by sector for fresh surface and groundwater in $10^6 m^3$ for the year 2015 [31].

Table 9: Fresh-surface and groundwater use by sector in Greece 2015 [31]

Total Fresh and non-freshwater abstraction in 10^6 m^3	
SECTOR	**10,814**
Public Water Supply	1,418
Agriculture, Forestry, Fishing	8,283
Out of which for Irrigation	*8,232*
Aquaculture	*:*
Mining and quarring	confidential
Manufacturing industry	126
Production of electricity (cooling)	confidential
Construction	:
Services	:
Private households	0.00

The following map shows the groundwater and surface water reserves, appearing as a blue net or dot, per water departments of the country. It is evident where the more shortage is [32].

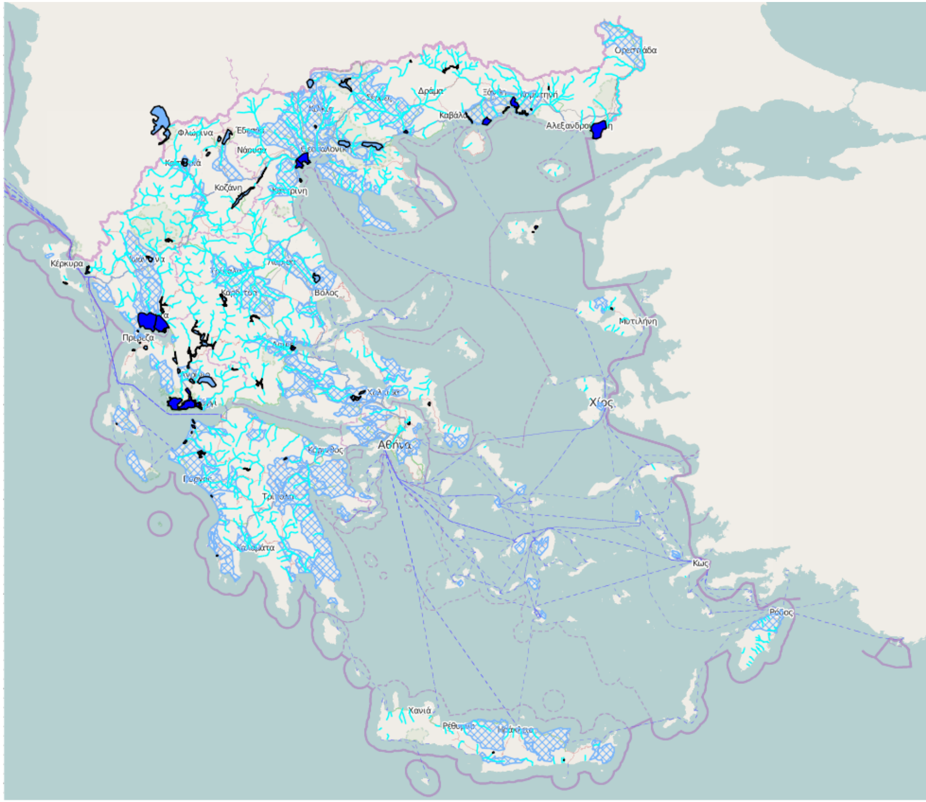


Figure 14: Ground water, surface water (rivers, lakes, transitional waters) per water district of Greece [32]

Greek water is being sorted geographically in fourteen water departments [33]:

1. West Peloponnesus
2. North Peloponnesus
3. East Peloponnesus
4. West Central Greece
5. Heperos
6. Attica
7. East Central Greece
8. Thessaly
9. West Macedonia
10. Central Macedonia
11. East Macedonia
12. Thrace
13. Crete
14. Aegean Islands

Freshwater is basically shipped to most of the arid islands as shown in the table below [34]:

Table 10: Fresh water imported in the most arid Greek islands for years 2010 up to 2014 [34]

Island	Fresh Water Quantity Imported per Year (m^3/y)				
	2010	2011	2012	2013	2014
Lipsi	55992	53934	69669	53707	16641
Chalki	54381	48555	47711	48560	2816
Megisti	37688	15444	24647	36347	23992
Kimolos	46488	46602	48107	52027	55340
Heraklia	16190	16839	17245	17298	14714
Schinoussa	28766	27054	17394	35309	19938
Koufonisi	49372	51614	53101	56461	51117
Donousa	15383	11781	8296	12602	10386

According to Report on Water Desalination Status in the Mediterranean Countries of 2012 there are installed 192 desalting plants in Greece with a total capacity of 149,250m^3/day, of which the 35 of 40135m^3/day are presumed online. The source of water is 55.79% seawater, 40.55% brackish water, 2.51% pure water, and 1.14% river water [35].

The following figures summarize all these plants by use, method, and water feed:

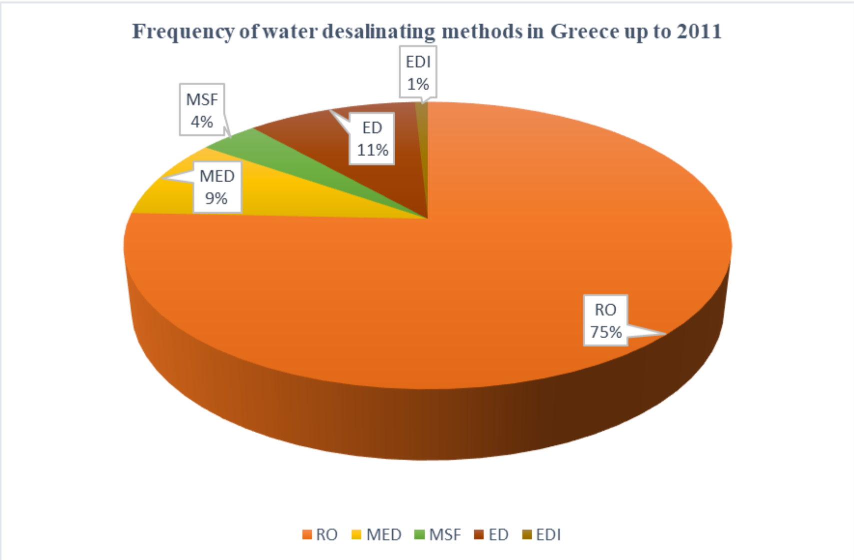


Figure 15: Frequency of water desalinating methods in Greece up to 2011 (data acquired from [35])

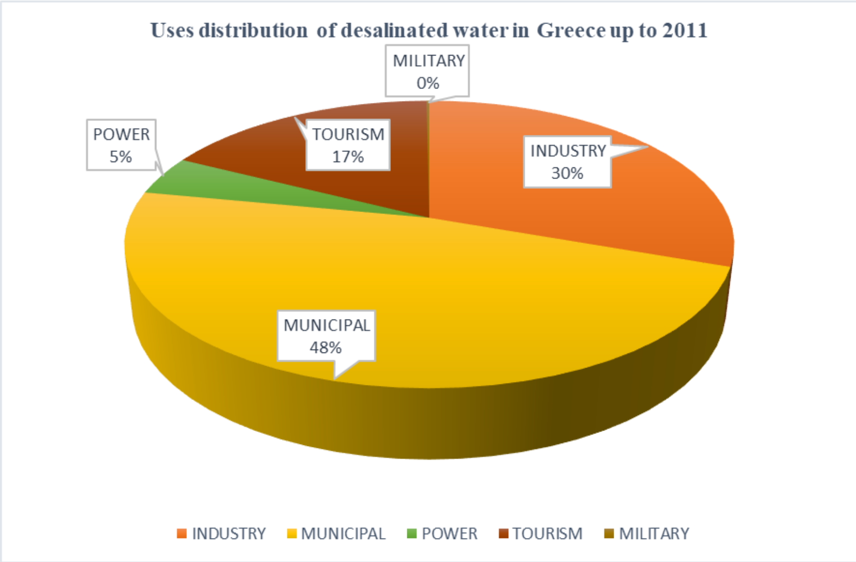


Figure 16: Uses distribution of desalinated water in Greece up to 2011 (data acquired from [35])

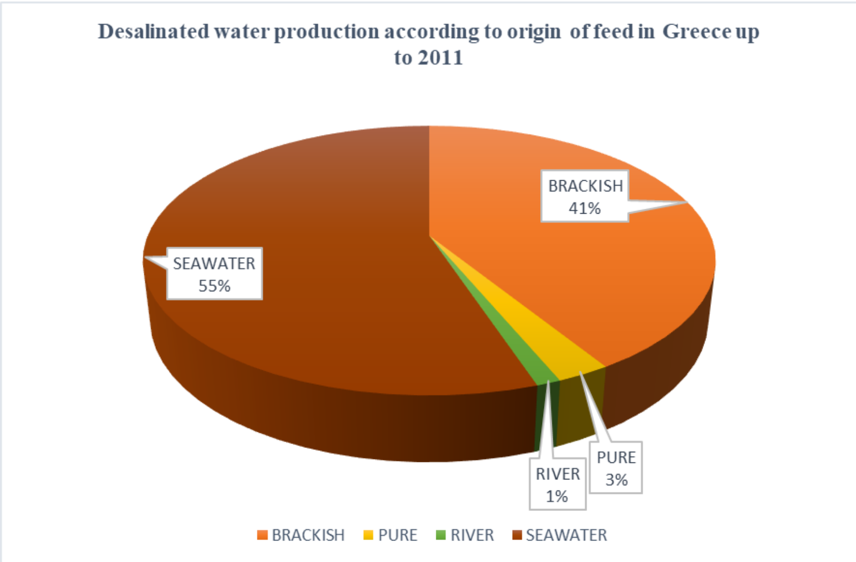


Figure 17: Desalinated water production according to origin of feed water in Greece up to 2011 (data acquired from [35])

The following chart shows a complete chronological order of the capacities of desalination plants in Greece up to 2016 [27].

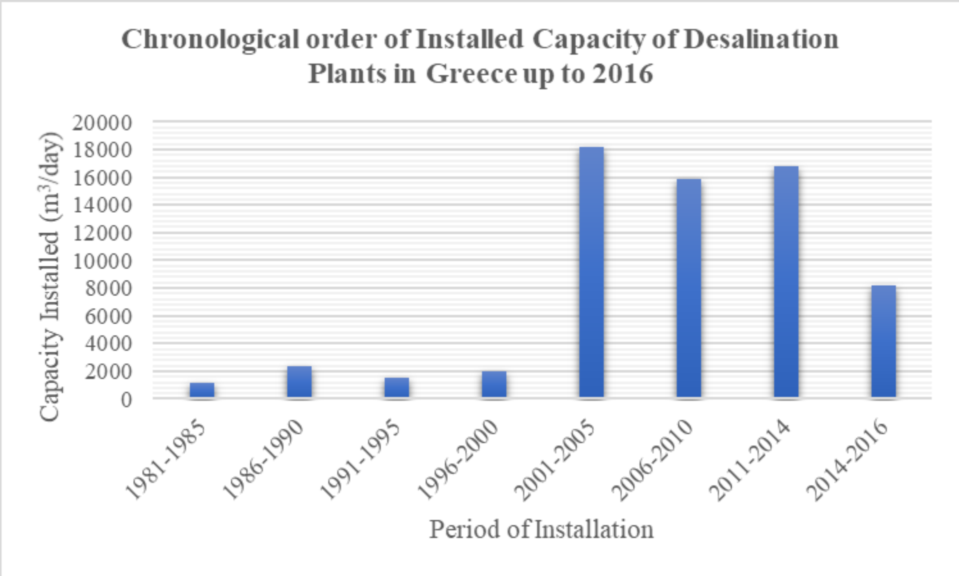


Figure 18: Chronological order of Installed Capacity of Desalination Plants in Greece up to 2016 [27]

In these plants there are included a few from the bellow table and in addition to these, other ones constructed and operating:

Table 11: Operating desalination plants 2014-2020 [36],[37],[38],[39],[40],[41],[42],[43]

Location	Method	Production m^3/day	Raw water	Year	Use	Constructor
Almiros, Malevizi, Crete	RO	2000	Brackish	2014	Municipal	Sychem
Paros	RO	2500	Seawater	2019	Municipal	Sychem
Heraclea, Cyclades	MSF	300 (1100 with storage tanks)	Seawater	2014-2020	Municipal	_
Hydra	_	1600	_	2014	Municipal	TEMAK
Mandraki	RO	400	_	2018	Municipal	Watera
Patmos	RO	500	Seawater	2017	Municipal	Watera
Kefalonia, Argostoli	RO	10000	Brackish	2019	Municipal	TEMAK
Kos	RO	700	Brackish	2019	Tourism	TEMAK

2.4 Climate Change and Desalination

Climate change is a phenomenon widely accepted by most of the scientific community and society. The causes and worldwide side effects of it will not be analysed in this dissertation. It is clear by now that climate change is real, and it is already happening even in the Mediterranean and small country of Greece. There have been a few studies and projections on what the impact is going to be but even without them it is evident that the weather phenomena are more intense and there is higher temperature during the summer season while dry periods are also more intense. So, how is that related to desalination? The answer is whether the freshwater needs are going to increase or not. But apart from that, Greece as a member of the European Union and having accepted the Paris Agreement is moving towards mitigation and adaptation strategies and decarbonization until 2028 [30],[44].

All studies lead to the same result: "Climate change will lead to reduced water availability in the future" [45]. The water supply sector will have to strain to meet the demand and simultaneously irrigation and therefore agriculture will be significantly affected. In a National Bank of Greece research "The impacts of water shortage on the water supply sector, including touristic and, in part, industrial uses, are examined. The impacts of reduced availability of irrigation water are taken into account in the examination of agriculture" and the adaptation cost of improving the efficiency of water abstractions is €68.4 million/year, with a benefit of €380 million/year [45].

Regarding temperature, an analysis was conducted on climate change impact through the years in the agricultural areas and touristic islands and the main results are that the islands are more susceptible to increase of the number of tropical nights per year. In addition to that the relative humidity in coastal areas is going to deteriorate comfortability for both locals and tourists. Another conclusion is that changes in the number of days with fire risk also tend to increase everywhere as well as for agricultural areas with trees (such as olive, orange, peach trees). In central Greece there are projected up to 20 more days of fire risk per year. As far as precipitation is considered, winter precipitation generally decreases while autumn precipitation is projected to increase in most agricultural areas [46]. So, it is more than evident that indirectly, but clearly fresh water will be more valuable soon.

The goal of Paris Agreement is for the countries that participate in it to achieve a climate change below 2 degrees Celsius global temperature increase. Greece as a Southern European country is going to face increased water shortages and land use change up to 10 to 20% and climate is responsible for this in 80-90%. The reductions in groundwater discharge are estimated for Greece in -810Mm^3/year. The following figure shows the water demand for the whole Europe where "projected land use changes and gross domestic product changes are taken into account in the water resources modelling and estimations of future water demand" [47]:

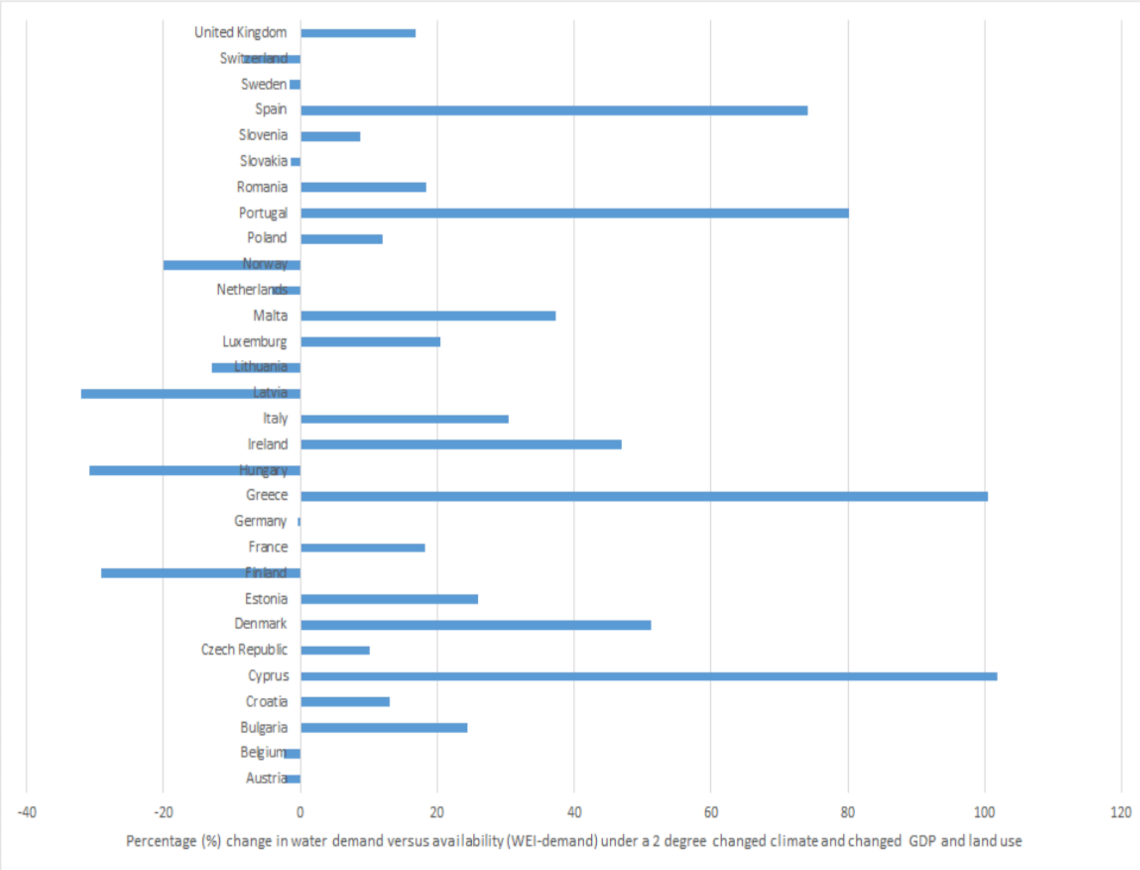


Figure 19: Percentage change in the average water demand-availability ratio (WEI) per country under a 2°C climate versus current climate [47].

2.5 Desalination Worldwide and island complexes

Worldwide, desalination is a sound and well-established technology. Up to June 2018 the total cumulative commissioned capacity was 97.4 million m^3/day globally [48]. Up to June 2017 there are over 150 countries to use this technology and to be precise, 18,426 plants are in operation worldwide supplying over 300 million people with 86.5 million cubic meters precious fresh water. But that stands for only 1% of the world's drinking water [4]. The preferred technology goes according to location and history. Oil-rich but water scarce regions, like in Middle East, utilize thermal technologies, and still prefer them to membrane ones. But the shift towards membrane technologies happened for many reasons and currently Seawater Reverse Osmosis stands at 65.5 million m^3/day, accounting for 69% of the volume of desalinated water produced [49]. The following figure is informative regarding the technologies installed worldwide:

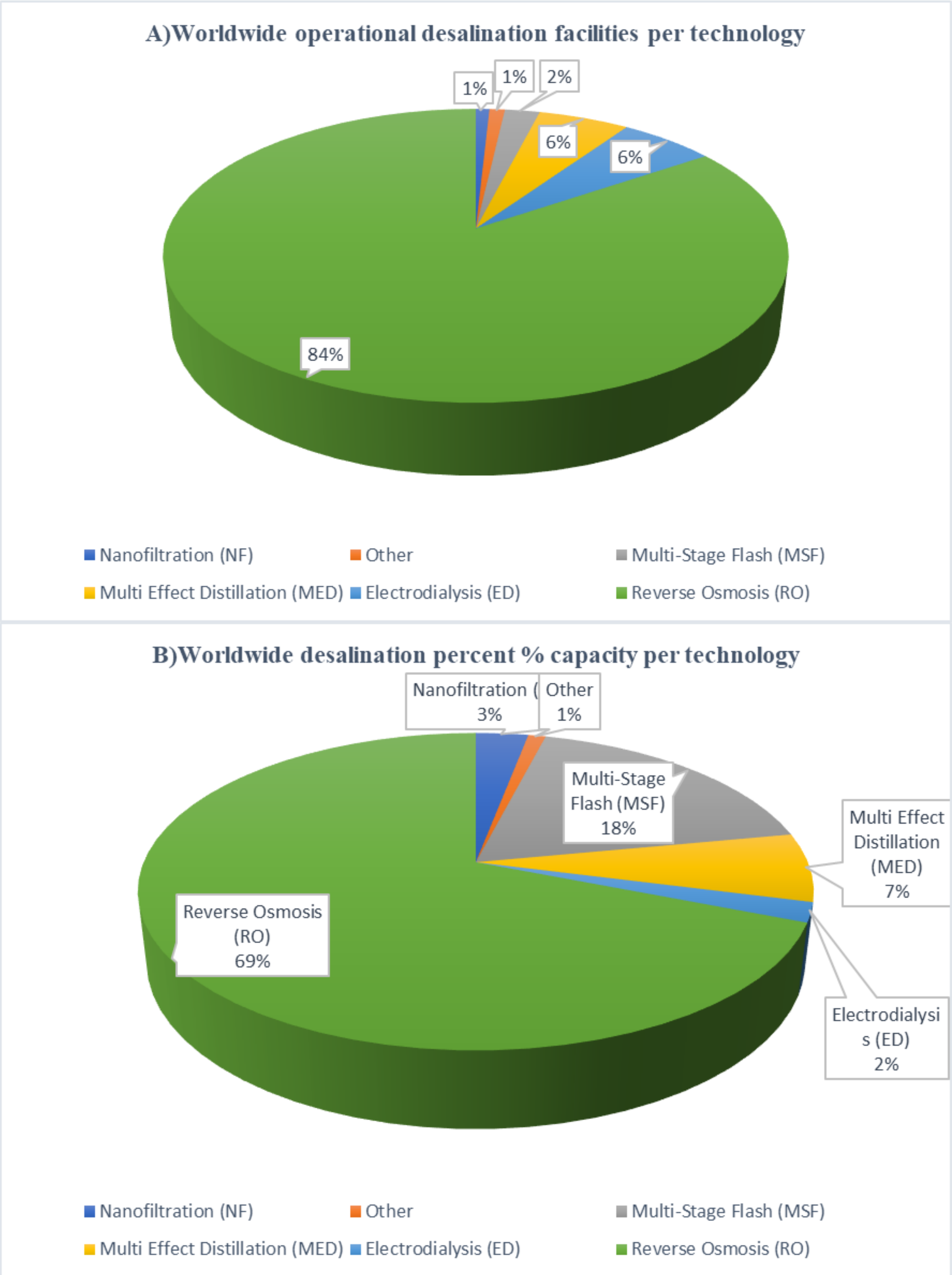


Figure 20: A)Number and B)Capacity of operational desalination facilities by technology Worldwide for 2019 [49]

It is quite clear that the richer the countries, the more water consumption, for municipal, industry and military use and the more the desalination plants. The following table and map depict the desalination plants by capacity, geography, use and income level [49]:

Table 12: Number, capacity and global share of operational desalination plants by region, country income level and sector use [49]

	Number of desalination plants	**Desalination capacity (million m^3/day)**	**(%)**
Global	15906	95.37	100
Geographic region			
Middle East and North Africa	4826	45.32	47.5
East Asia and Pacific	3505	17.52	18.4
North America	2341	11.34	11.9
Western Europe	2337	8.75	9.2
Latin America and Caribbean	1373	5.46	5.7
Southern Asia	655	2.94	3.1
Eastern Europe and Central Asia	566	2.26	2.4
Sub-Saharan Africa	303	1.78	1.9
Income level			
High	10684	67.24	70.5
Upper middle	3075	19.16	20.1
Lower middle	2056	8.88	9.3
Low	53	0.04	0
Sector use			
Municipal	6055	59.39	62.3
Industry	7757	28.8	30.2
Power	1096	4.56	4.8
Irrigation	395	1.69	1.8
Military	412	0.59	0.6
Other	191	0.9	0.4

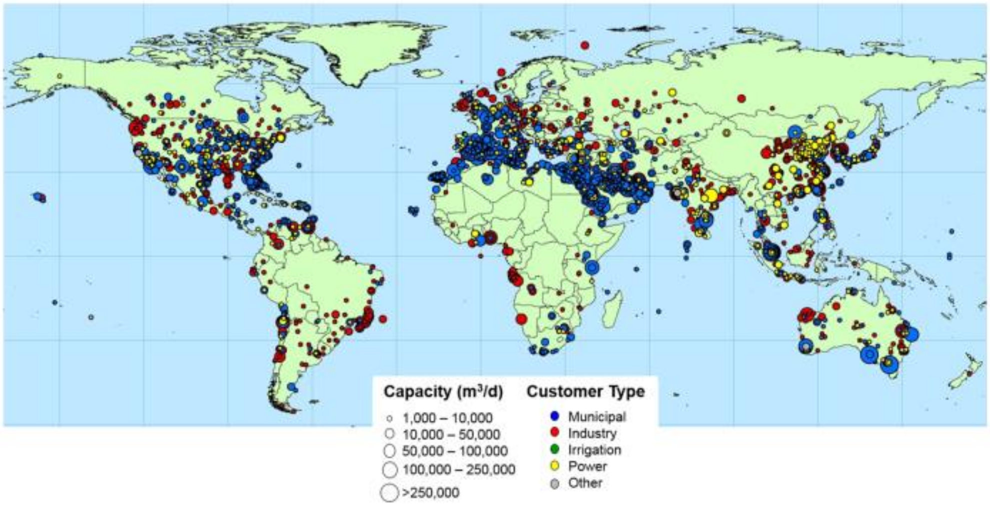


Figure 21: Global distribution of operational desalination facilities and capacities (>1000m^3/day) by sector user of produced water [49]

What is more interesting though is to compare the like Greece countries that consist of island complexes, are very dependent on weather and tourism like the Maldives, Caribbean, Bahamas, Barbuda etc. The International Renewable Energy Agency conducted a study in 2015 for Renewable Desalination Technology options which focuses mainly on small island developing states (SIDS) that are climate change vulnerable and need new technologies. So, for Antigua and Barbuda, Bahamas, Barbados, Cuba, Dominican Republic, Saint Lucia, Saint Vincent and Grenadines, Trinidad and Tobago, Capo Verde, Comoros, Maldives, Mauritius, Seychelles, Fiji, Kiribati, Marshall Islands and Papua New Guinea the desalination capacity by technology is shown as follows [50]:

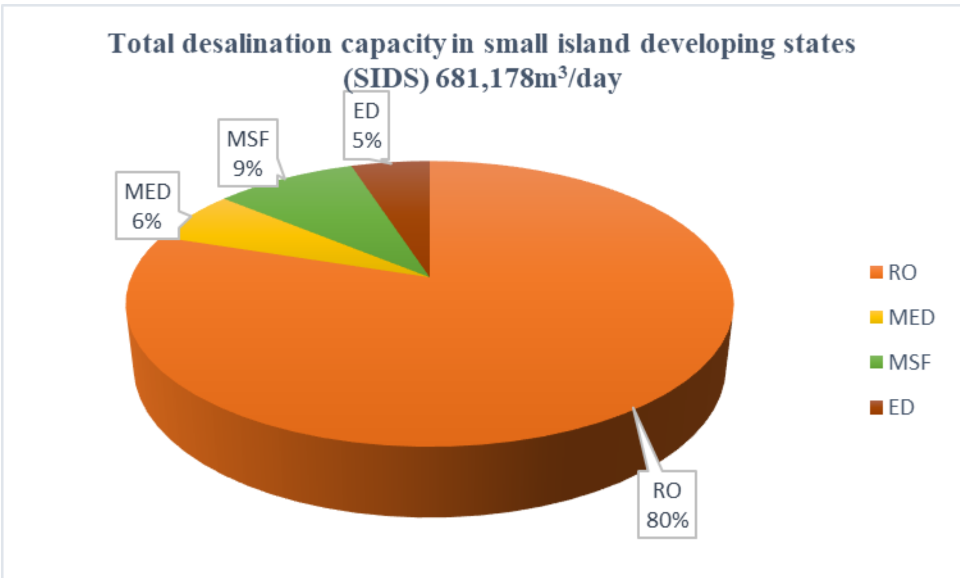


Figure 22: Desalination Capacity shares by technology in SIDS [50]

In the case study there was a choice of islands of these complexes, including Mykonos in Greece, that have similar characteristics shown in the following table [50]:

Table 13: Characteristics of selected islands of worldwide island complexes [50]

Island/ Ocean	Population (per 1000)	Size (km^2)	Topology	Economic Sectors	Desal. Capacity (m^3/day)
Cabo Verde/Atlantic	516	4300	Volcanic, Steep, mountains	Remittances, Tourism	82000
Mykonos-Greece/Mediterranean	10	105	Rocky, small mountains	Tourism	8200
Antigua Barbuda/Caribbean	85.6	440	Flat, coral limestone	Tourism	85000
Grenada/Caribbean	105.5	340	Volcanic, central mountains	Tourism	500
Kiribati/Pacific	103	810	Flat, coral atoll	Copra, international aid, tourism	210
Vanuatu/Pacific	243.3	12190	One large volcano	Agriculture Fishing, offshore financial services, tourism	192

The result of the case study is that Reverse Osmosis is generally technologicaly mature and proven to be economicaly viable in the longterm. It is electricity driven, can be installed in smaller climax or be portable, is very comfortable in cases of tourism since every hotel can install a small RO facility whithin its territory with relatively small cost.

There was also conducted a case study on the feasibility of coupling Fossil Fuel dependent Desalination technologies with Renewable Energy sources in these island complexes, taking into acount both technical and economical parapeters. The following figure depicts the possible combinations of these technologies [50]:

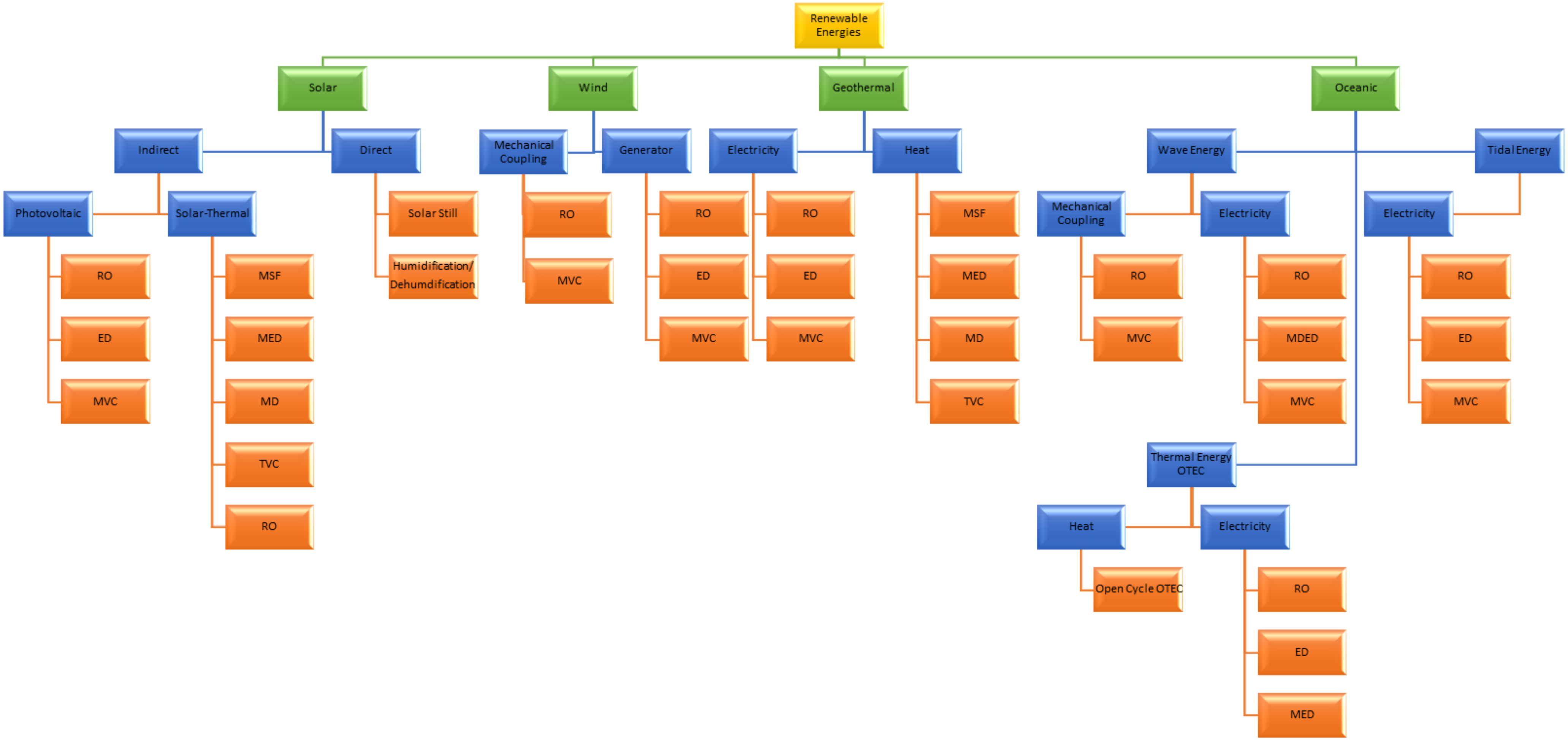


Figure 23: Possible Combinations of Renewable Energy and Desalination Technologies [50]

Out of all these combinations, there was a selection according to technological maturity, capacity range, technological viability, which is the following:

- RO+PV either grid connected, off-grid with batteries 24h operation and 7h operation.

- RO+CSP
- MED+CSP
- RO+Wind either on or off-grid

The main result is that, depending on the location of the resources and cost of fossil fuel on the island, Renewable desalination can be cost-competitive compared to the fossil fuel one. Reverse Osmosis coupled with Photovoltaics or Wind as well as Multi Effect Distillation run by Concentrated solar power, are combinations that reduce the water cost significantly. Regarding the grid connection when available, renewable energy systems can also be installed to reduce the fossil fuel dependency.

3 Desalination, cost defying and fossil fuel dependent

In this chapter there is an explanation of why this technology is highly dependent on fossil fuels. In addition, there are presented costs of several desalination plants both worldwide and in Greece, resulting to why the main product water can be expensive. The goal of this chapter is to conclude to the optimal technology for Greek arid islands in terms of both economy and fossil fuel independence.

3.1 Cost inefficiency

Desalination is cost-ineffective. There are a few factors that are common for all desalination plants that affect costs. Apart from the technology choice, energy cost, location, plant size capacity and configuration, feedwater, product water quality, and environmental compliance requirements are those factors. The latter depends on the country and the policies it has set. There is going to be a reference on these factors and their consequences on each technology chosen [4].

3.1.1 Representative costs worldwide

The following representative costs are based on sixty (60) desalination plants of different capacity, configuration, and technology worldwide that are built during the past twenty (20) years. Costs are initially in US dollars and the 2016 currency because they are worldwide. They are converted in Euros according to the 2016 average exchange rate that equals to 0.8979 €/USD$ [51]. The capacity is given in Million Liters of Desalinated water or $1000m^3$or km^3. These plants also differ in quality of feedwater and environmental regulation. The capital cost includes the purchase cost of major and auxiliary equipment, land, construction, management overheads, contingency costs. Annual running costs required for this analysis are energy, labor, chemicals, consumables, and spare parts [4]. Typical costs for Multistage Flash Distillation (MSF), Multi-Effect Distillation (MED), Seawater Reverse Osmosis (SWRO) as well as Hybrid plants, are given in the following table that consists of three parts [4]:

Table 14a: Typical costs of MED and MSF desalination plants worldwide [4]

Plant name and location	**Operation year**	**Size(km^3)**	**Capital cost (million €)**		**Operation and Maintenance (O&M) cost (million €/year)**		**Cost of water (€/m^3)**
			Total	**Per km^3**	**Total**	**Per km^3**	
MED and MSF							
Arzew, Algeria	2002	88.9	179	2.01	8.89	0.10	1.56
Taweelah A1, Un. Arab Emirates	2003	146	320	2.19	14.91	0.10	1.50
Sohar, Oman	2007	150	424	2.83	21.46	0.14	1.39
Ras Laffan 2B, Qatar	2008	272	612	2.25	28.10	0.11	1.34
Shuweihat S1, United Arab Emirates	2004	378	726	1.92	31.61	0.08	1.29
Shuweihat S2, United Arab Emirates	2011	459.1	865	1.89	36.36	0.08	1.22
Yanbu Ph3, KSA	2016	550	898	1.63	46.87	0.08	1.15
Shuaibah 3 IWPP, KSA	2010	880	1473	1.67	61.87	0.07	0.92
Tobruk (extension), Libya	2014	13	22	1.71	0.99	0.07	1.35
Rabigh, KSA	2005	25	52	2.10	2.07	0.08	1.31
Abutarab, Libya	2007	40	63	1.57	2.51	0.06	1.28
Zuara, Libya	2010	40	54	1.34	2.15	0.05	1.30
Layyah, United Arab Emirates	2007	48	62	1.30	2.33	0.04	1.28
Ras Al Khaimah, United Arab Emirates	2005	68	89	1.31	2.96	0.04	1.26
Sussa Derna Zawia, Libya	2009	160	193	1.20	6.64	0.04	1.25
Al Hidd, Bahrain	2008	273	288	1.06	8.53	0.03	1.24
Ras Laffan, Qatar	2010	286	329	1.15	9.16	0.04	1.21
Marafiq Jubail IWPP, KSA	2009	800	1001	1.25	40.23	0.05	1.01

Table 15b: Typical costs of Reverse Osmosis desalination plants worldwide [4]

Plant name and location	**Operation year**	**Size (km^3)**	**Capital cost (million €)**		**O&M cost (million €/year)**		**Cost of water (€/m^3)**
			Total	**Per km^3**	**Total**	**Per km^3**	
Reverse Osmosis							
Mediterranean Sea							
Moni, Cyprus	2009	20	32	1.59	4.85	0.24	0.90
Larnaca, Cyprus	2009	62	72	1.16	12.48	0.20	1.13
Joft Lasfar, Morocco	2013	75.8	151	1.99	12.84	0.17	0.99
Cap Djinet, Algeria	2007	100	133	1.33	16.07	0.16	0.82
Fouka, Algeria	2008	120	176	1.46	17.78	0.15	0.81
Hamma, Algeria	2008	200	244	1.22	29.00	0.14	0.82
Ashdod, Israel	2011	320	399	1.25	40.05	0.13	0.70
Magtaa, Algeria	2009	500	460	0.92	49.74	0.10	0.61
Sorek, Israel	2013	624	431	0.69	52.26	0.08	0.57
Barcelona, Spain	2009	200	290	1.45	35.47	0.18	0.93
Larnaca, Cyprus	2001	64	72	1.12	11.85	0.19	0.86
San Nicolas, Canary Islands	2001	5	8	1.54	1.98	0.40	1.59
Arabian Gulf and Sea of Oman							
Sohar, Oman	2013	20	27	1.35	6.73	0.34	1.72
Palm Jumeirah, United Arab Emirates (UAE)	2008	64	106	1.65	16.25	0.25	1.38
Ghalilah, UAE	2015	68.2	76	1.10	14.82	0.22	1.36
Sur, Oman	2010	82.2	130	1.58	16.34	0.20	1.07
ROI Majis, Oman	2014	20	45	2.23	3.32	0.17	1.13
Al Jubail (4), KSA	2014	100	152	1.52	17.87	0.18	1.05
Shuwaikh (2), Kuwait	2010	136	189	1.38	22.36	0.16	1.04
Al Dur, Bahrain	2012	218	228	1.05	26.31	0.12	0.86
Red Sea							
Yanbu, KSA	2016	30	61	2.03	8.82	0.30	1.53
Kaust, KSA	2017	40	74	1.84	12.75	0.32	1.44
Shuaibah (3) Extension, KSA	2011	150	246	1.64	26.94	0.18	1.12
Shuqaiq, KSA	2010	212	256	1.20	30.89	0.14	1.08
Jedda 3, KSA	2013	240	290	1.20	33.04	0.13	1.02
Atlantic/Pacific Ocean							
Carlbad, CA	2015	200	435	2.17	8.82	0.24	1.50
Corpus Christi, TX	In planning	45	106	2.36	6.02	0.13	1.08
Santa Barbara, CA	2016	10	40	4.02	3.68	0.37	2.24
Singspring, Singapore	2005	136	159	1.17	21.01	0.15	0.79
Sydney, Australia	2010	250	1716	6.86	47.50	0.19	2.57
Jaffna, Sri Lanka	In plan	24	45	1.87	3.68	0.15	0.99
Durban, South Africa	In plan	36	69	1.92	5.93	0.16	1.04

Table 16c: Typical costs of Hybrid desalination plants worldwide [4]

Plant name and location	Type	Operation year	Size(km^3)	Capital cost (million €)		O&M cost (million €/year)		Cost of water (€/m^3)
				Total	Per km^3	Total	Per km^3	
Yanbu, Phase-1, KSA	MSF	1995	181.7	312	1.72	29.09	0.16	1.23
	SWRO		127.9	157	1.23	36.81	0.29	1.01
Jeddah, 1&2, KSA	MSF	1994	363.4	603	1.66	50.82	0.14	1.04
	SWRO		136.4	169	1.24	34.12	0.25	0.98
Fujairah 1, UAE	MSF	2004	283.5	557	1.97	14.99	0.05	1.06
	SWRO		170.5	181	1.06	16.70	0.10	0.92
Fujairah 2, UAE	MED	2010	455	646	1.42	20.11	0.04	1.00
	SWRO		136	160	1.18	13.20	0.10	0.94
Ras Al Khair, KSA	MSF	2014	727.4	952	1.31	33.04	0.04	0.85
	SWRO		309.1	337	1.09	27.57	0.09	0.76

Multistage Flash Distillation plant size is closely related to cost of water. Generally, the bigger the plant, the lower the cost. The larger the plant, the lower the capital cost per km^3 of Desalinated freshwater because of economies of scale. Also, Operation and Maintenance costs per year are relatively lower. When these plants are combined with power projects they have proved cost-competitive [4].

Multi-Effect Distillation Desalination projects typically produce water at lower cost for smaller plants than MSF, and for larger facilities they are comparable. When the capacity needed is less than 100 km^3, MED is preferred to MSF because they are more energy efficient. Especially for the high salinity waters of the Middle East, there is a growth of MED technology. But in general, investors tend to prefer MSF facilities thanks to the technology maturity and lower risks [4].

Reverse Osmosis Desalination plants (SWRO) are the most prone to factors mentioned above affecting their costs. But in general, costs decline as capacity increases, while above 100 km^3 of capacity, they increase. Sometimes special delivery conditions and subsidies, and operation are simply the conditions that affect the costs. But there are examples of very large plants (>500 km^3) that reduced them significantly several years later after the initial operation of the plant. They achieved it by combining innovative technology and adjusted the price of water from low initial cost to higher. There are also examples of facilities operating under stringent environmental requirements or functioning as a standby one, and with very high labor cost due to country they are in, that can give valuable information that should be avoided from newer installations. Advances in technology in all stages have contributed to lowering such costs even when located in areas with higher salinity and warmer waters [4].

Hybrid plants are a combination of thermal and membrane technologies, usually MSF with SWRO, and aim to reduce energy demands. Usually, two-thirds of the total volume of product water result from the thermal technology and one third from membrane one. The cost competitiveness is a result of efficient energy use and economies of scale. These plants are highly dependent on site-specifications such as local power, water demands conditions and project size. The energy efficiency stems from RO system using warm cooling water from the thermal desalination plant. Especially when large seasonal variations in power demand, along with constant one for desalinated water throughout the year, hybrid plants are competitive. Because power generation plants are constructed at a high distance from centers of water demand or from sites suitable for desalination capacity, the transport surplus of power and water to the final users often leads to costs that equalize the cost efficiency of hybrid plants [4].

3.1.2 Factors affecting costs and desalination technologies comparison

Overall, thermal desalination technologies are capital-intensive while membrane ones are operational expenses intensive. Between thermal categories MSF capital costs are higher than MED plants. The membrane technologies are riskier for the investors since they are prone to many costs (engineering, administration, regulation, and legal procedures during construction), while they are design intensive. The following figure summarizes the typical costs of the technologies. The conclusions are explained for each factor separately [4].

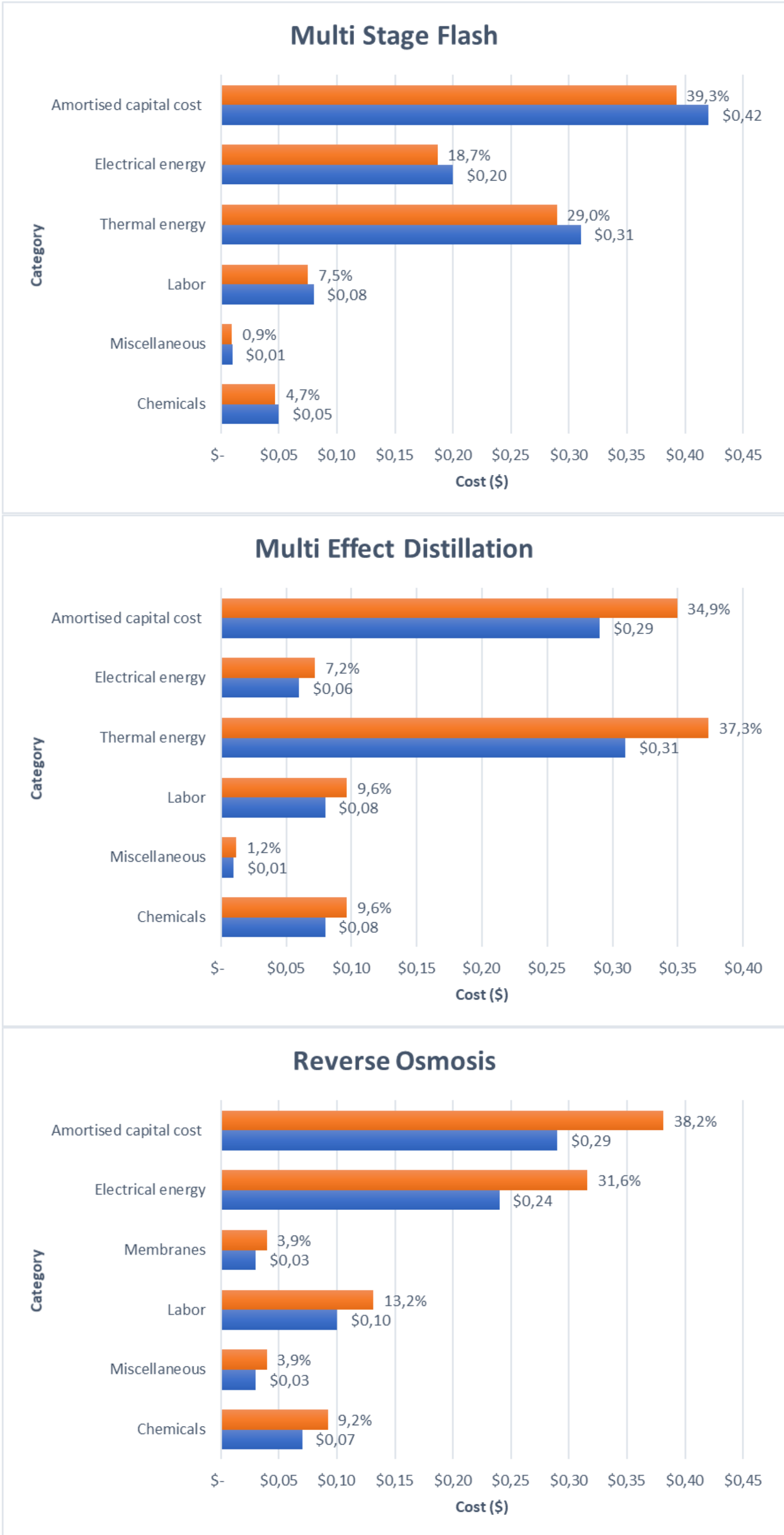


Figure 24: Summary of percentage of typical costs for Desalination technologies [4]

Energy

Both thermal and electrical energy is required for thermal technologies, making them more sensitive to energy costs. About two-thirds up to three-quarters of all recurrent costs is the energy cost for MSF and MED plants, while for SWRO, it fluctuates from one-third up to one-half of the total. But another fact is that for SWRO plants, electricity needs are excessively high since it is the only energy source [4].

Location

Seawater desalination is typically more viable when located near the coast and at a lower elevation. A 100-meter vertical lift almost equals the cost of horizontal transportation of water for 100-kilometer. But when comparing freshwater transport to desalination to cover the high demand, the second option, thanks to progression, and innovation becomes more competitive [4].

Plant Size and Economies of Scale

All desalination technologies must cope with scaling. But for each technology, there are different patterns of returns to scale formed by the optimal size of the treatment units, the physical footprint on the plant, the flow distribution requirements, and the intake and outfall configuration. Generally, thermal desalination plants are favored from scale, while for SWRO at a higher capacity, the benefits of scale decrease. The optimum size for SWRO is from 100 km^3 to 200 km^3 [4].

Feedwater Quality

The more sensitive technology to feedwater is Reverse Osmosis. Salinity, boron content, temperature, and membrane biofouling potential have an impact on the design and operations of these plants, and consequently, on both capital and operating costs. The pre-treatment may consist of dissolved air flotation clarifiers and granular media of membrane filters. If the salinity of feedwater is relatively low and temperature is milder, then the energy requirements also reduce, and in the end, costs reduce as well. That is why in Mediterranean Sea and similar waters like in the Caribbean Islands, SWRO is the optimum choice for thermal technologies because of lower costs. Seawater Reverse Osmosis is blooming in these areas. Membrane performance is also affected by changeable salinity. So, in areas with large seasonal flows or risk of mixing freshwater with feedwater, problems may occur. The pre-treatment design will be more complex and costly. Additional pre-treatment may be required due to concentration and particulate, colloidal, and dissolved organic foulants in source seawater. Temperature affects the feed pressure. The higher the feedwater temperature, the higher the need for two-pass membrane treatment, and the higher the construction and operation costs. Finally, there are many areas, with SWRO desalination plants, where there are heavy algal blooms, and the content of easily biodegradable organic substances is higher. The latter increases the risk of biofouling, the phenomenon of membranes plugged by a thick biofilm formed when the algae consume the organic content. Such plants need multiple clarification and filtration facilities in series, skyrocketing the capital, operation, and maintenance costs [4].

On the other hand, thermal technologies evaporate pure water and discard all other elements. But they are prone to the buildup of scales caused by evaporation. So, the use of anti-scalants is necessary. Apart from that, in thermal plants the corrosion caused by the product water of high pH , must be prevented, along with the corrosion of heat exchangers. The solution is high corrosion-resistant and costly materials like titanium, that are much more expensive than RO membranes made of polymers. At high-salinity waters, thermal technologies take the lead since they result in comparable or lower energy consumption than SWRO. In general, thermal technologies are more competitive where high salinity, boron content, and biofouling risk are present [4].

Target Product Water Quality

As mentioned in previous chapter, thermal desalination technologies produce product water of better quality than membrane ones because the levels of salt, boron and bromide are much lower. Reverse osmosis needs enhancement to produce such water, increasing costs. But in both cases, desalinated water needs anticorrosion treatment and disinfection. Desalinated water goes through pH adjustment, remineralization, and disinfection. Treatment is done with calcium-based compounds for hardness, chemicals (CO_2) that add alkalinity to protect the distribution system, and chlorine for disinfection. In that way, the product water is potable according to World Health Organization guidelines. The costs of post-treatment are a higher burden for membrane technologies [4].

Environmental Impacts and the Effect of Regulation

There are two types of impacts on the environment, direct and indirect. The marine environment is directly affected by desalination when:

1. the source water contains a host of aquatic organisms (algae, plankton, fish, bacteria etc.) is used in bulk quantities, causing an imbalance of the local marine ecosystem

because there can be sucking right into the facility or entrapment of these organisms, and

2. the plant discharge may contain brine that elevates salinity, temperature, treatment chemicals, and especially for thermal plants, heavy metals used for anti-corrosion.

These impacts are subjects of regulations and affect a lot the cost of mitigating to them. The first case is practically easier to mitigate, usually by reducing the entrance velocity or installing screens to reduce the impingement of organisms. But especially the second case is subject to strict regulations since it can damage local ecosystems. Brine disposal must happen very carefully, and to minimize the harm one option is to reintroduce it to the ecosystem where it is rapidly diluted or mixed with another stream when entering the ocean. This challenging disposal is very different for thermal technologies and membrane ones. In terms of volume, salinity, and temperature, brine differentiates. Therefore, thermal plants are near the sea. Because the brine volume may be up to 4 times higher than in membrane technologies, the temperature is higher, but the salinity is much lower. On the other hand, brine from SWRO plants needs more elaborate processing because even in much smaller quantity its salinity is very high, and it may contain many chemicals. These plants are more efficient in brine disposal to the inland, especially when using brackish water instead of seawater. The table below summarizes the cost of brine disposal for different facilities with several methods [4].

Table 17: Concentrate disposal method and construction cost [4]

Concentrate disposal method	**Disposal construction cost (€/m^3/day)**
New surface discharge (new outfall with diffusion)	45-670
Colocation of desalination plant and power plant discharge	9-27
Co-disposal with wastewater treatment plant discharge	27-135
Sanitary sewer discharge	4-135
Deep/ Beach well injection	180-561
Evaporation ponds	270-4040
Spray irrigation	180-900
Zero liquid discharge	1350-4490

3.2 Fossil fuel dependency

Desalination fossil fuel dependency possible solution is renewable energies. But that is not always feasible for existing plants. The higher the feedwater salinity, the more energy-intensive the process is, and in the long-term, the more expensive the fuels. Apart from the additional threatens of climate change, greenhouse gas emissions, and severe environmental impacts of fossil fuel dependency, clearly from the economic perspective, the tendency towards sustainability results in long-term cost-effectiveness.

The plant should be very carefully designed, in coastal areas where renewable sources and water access are easier to facilitate. Also, in the case of solar energy a lot of land is required. So far, some typical costs of renewable energy desalination systems are shown in the following table[18]:

Table 18: Typical cost of the renewable energy desalination systems [18]

	Solar thermal energy			**Solar electrical energy**			**Wind Energy**	
Desalination technique	MED	HDH	SD	ED	RO	MVC	RO	RO
Capacity (m^3/d)	>5000	>100	>1	>100	>100	>100	>50	>1000
Cost (€/m^3)	2.2-2.7	2.5-6.3	1.3-10.8	10-11.3	11.2-15.1	5-7.5	6.3-8.8	1.9-5

In more detail, Concentrated Solar power is not cost-competitive compared to either conventional sources or other renewables such as wind and photovoltaics. But the potential for development along with environmental advances thanks to significant reduction in brine disposal, is very promising. According to estimations, the cost of solar-powered thermal desalination is going to be just up to 60% of what it is now by 2025, as by 2050, it might reach almost the half of it 0.90USD/ m^3 or 0.75€/m^3 [4]. The following table and figure summarize the total annualized cost of concentrated solar power desalination as well as the levelized cost of electricity potential for reduction by 2025:

Table 19: Total Annualized Cost of Desalinated Seawater Using Concentrated Solar Power [4]

	CSP-MED	**CSP-SWRO**
Mediterranean Sea	1.97-2.08	1.5-1.74
Red Sea	1.87-1.96	1.56-1.66
Arabian Gulf	1.77-1.89	1.78-1.87
The costs assume a hybrid plant with a solar share of 46% to 54%, project life of 25 years, and discount rate of 6%. The energy costs for SWRO and MED were calculated based on the opportunity cost of fuel at the international price and the fuel escalation cost of 5 %/year. Unit = USD$/$m^3$		

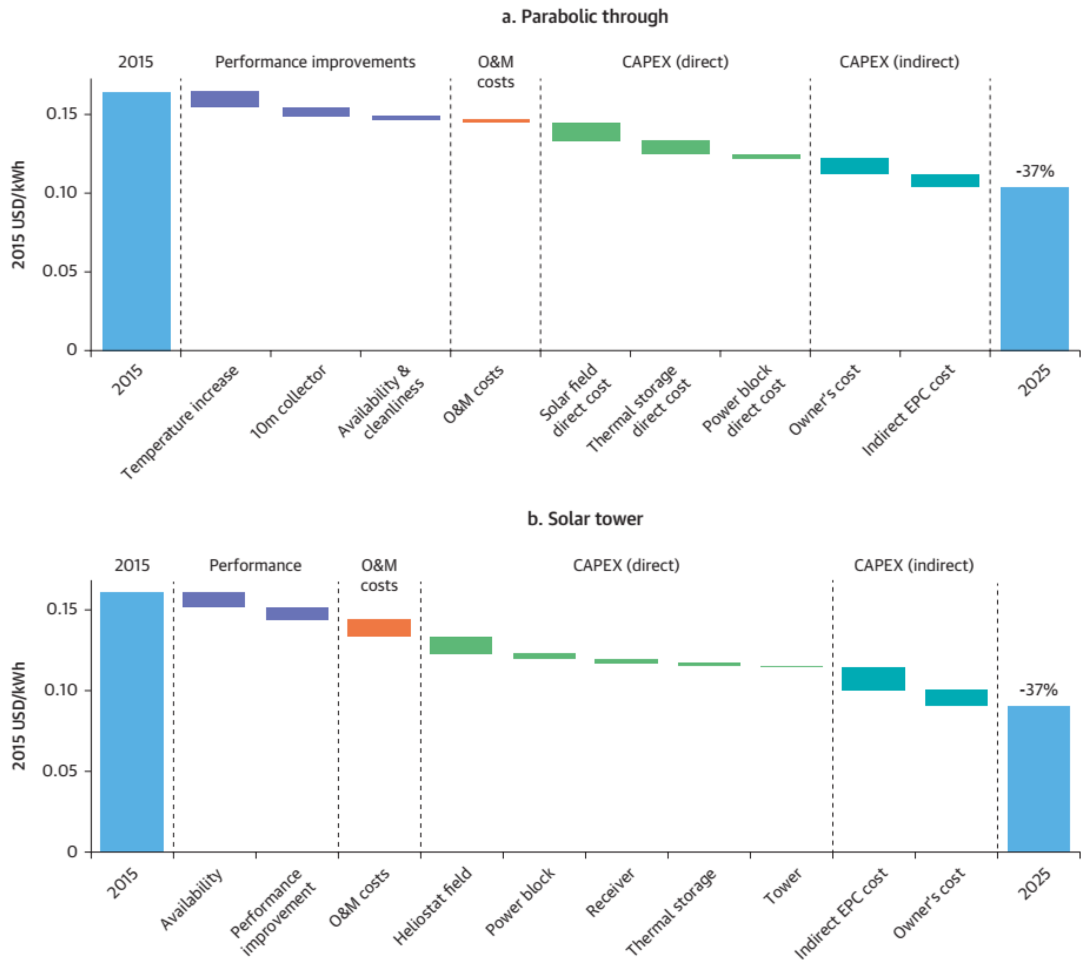


Figure 25: Global Concentrated Solar Power Levelized Cost of Electricity Potential for Reduction by 2025 where CAPEX is Capital Expenditure [4]

The costs of Table 19 are comparable to most of costs of Table 14a, meaning that concentrating solar energy MED desalination plant can be cost-effective.

3.3 Freshwater and Costs in Greece

Most desalination plants in Greece (74.41%) utilize Reverse Osmosis technology. Unfortunately, renewable desalination is not that prevalent yet. Reverse Osmosis coupled with Wind turbines in the island of Milos produced 3,360m^3/d freshwater at a cost of 1.80€/m^3. Another Multi-Effect Distillation geothermal plant installed there produced water had a cost of 1€/m^3. Also, a demonstration MED geothermal unit in Kimolos island had a capacity of 80m^3/day fresh water at a cost of 1.7€/m^3. Since these are not representative, the following graph depicts the costs of Reverse Osmosis fossil fuel-based desalination plants in Greece [5]:

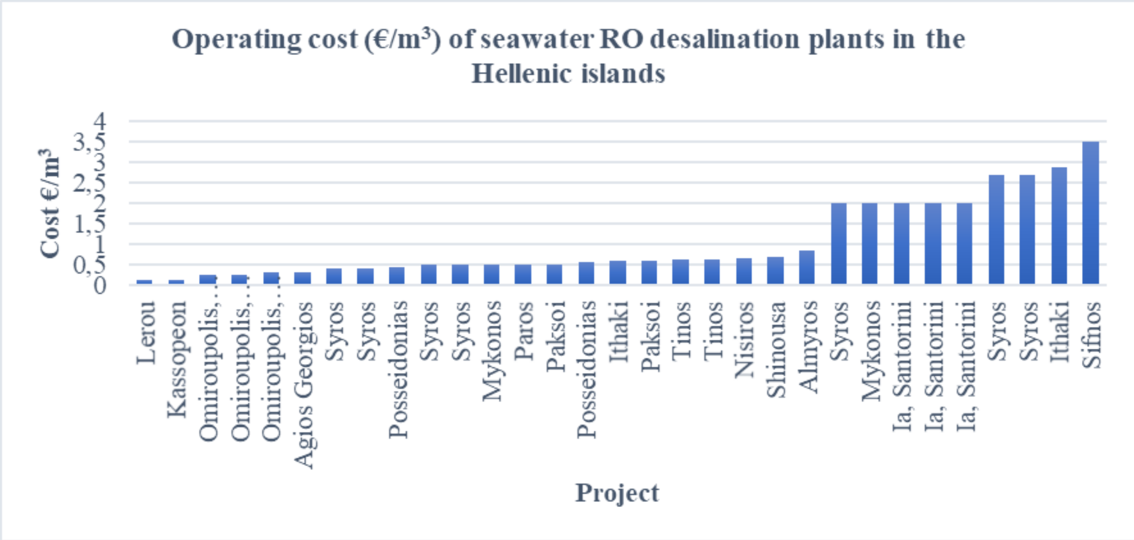


Figure 26: Operating cost (€/m^3) of seawater RO desalination plants in the Hellenic islands [5]

The average cost of RO desalination is 0.85€/m^3. According to sensitivity analysis in three arid islands with three different interest rates:

1. the water selling price when produced by fossil fuel desalination is presented in the following graph [52]:

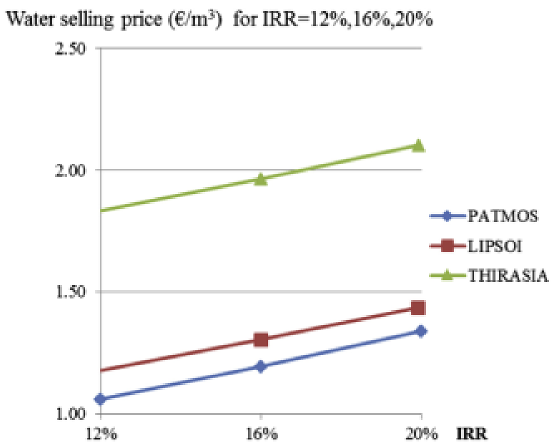


Figure 27: Water selling price based on fossil fuel desalination on three arid Greek islands [52]

2. The renewable energy desalination water has a slightly higher selling price according to the following table[52]:

Table 20: Proposed water selling price for the suggested islands [52]

Selected islands	Desalinated water production cost (€/m^3)	Water selling price (€/m^3)
Patmos	1.17	1.59
Lipsoi	1.41	1.88
Thirasia	2.18	2.57

3. The price of water, in any case, is a lot more efficient than the cost of water transported to the islands, as shown in the following graph [52]:

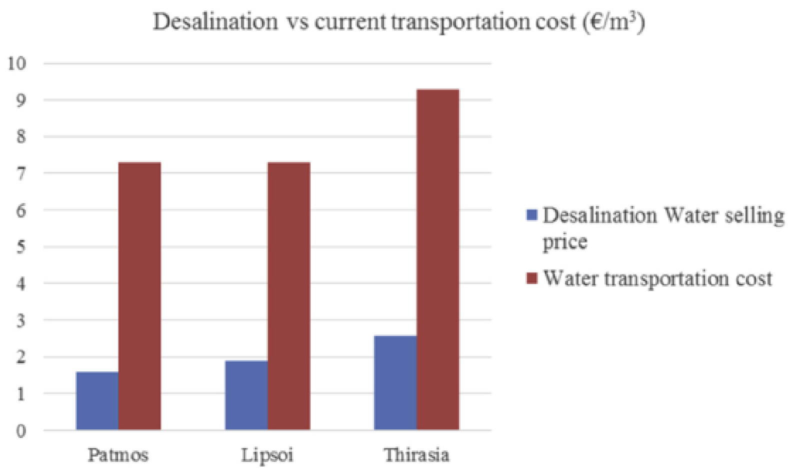


Figure 28: Comparison between desalination price and price of transported water [52]

The analysis concludes that desalination, coupled with renewable energy, is the most suitable solution whatsoever. The potential of these islands, for renewable energy sources, should be utilized, since the already existing power systems are overloaded. The water demand is fully covered and does not only replace the shipments. The lifetime of such a unit is 20years.

Another study conducted for the island of Syros and the city of Hermoupolis, concludes that the water cost of desalination drops with the installation of renewable energy sources as shown in the following graph [27]:

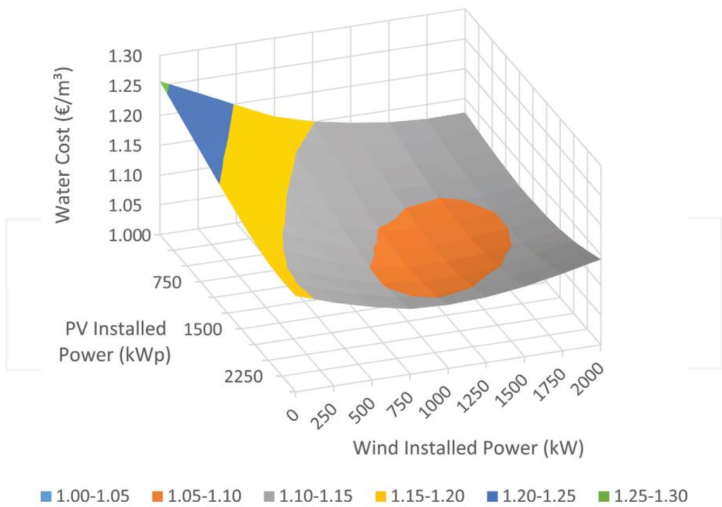


Figure 29: Water cost versus wind and photovoltaic installed power for Hermoupolis when both technologies exist simultaneously [27]

Water desalination with renewable energy sources is the most promising solution for the case of Greek arid islands and can significantly improve both government expences and water availability at any time.

3.4 Optimum desalination technology selection

This dissertation aims to design an energy and cost-efficient desalination unit. Whether the technology will be thermal, or membrane depends on the requirements of the arid Greek islands. Those are:

- A facility with a long lifetime,
- Easily integrated with renewable energy sources,
- An investment that will be reliable,
- Does not require much maintenance due to the proximity of the island.
- Simple pre- and post-treatment of water
- High product water quality

In other words, it should be an investment that will have a certain quality and will last.

The following table compares the three most competitive methods [53]:

Table 21: Comparison of the three most competitive desalination technologies for the Greek islands [53]

Energy Used	**Thermal**		**Electric**
Process	**MSF**	**MED**	**RO Membrane**
State of the art	Commercial		
Heat Consumption (kJ/kg)	250-330	145-390	-
Electricity consumption (kWh/m^3)	3-5	1.5-2.5	8-15
Plant cost ($/m^3/d)	1500-2000	900-1700	900-1500
Time to commissioning (months)	24	18-24	18
Production unit capacity (m^3/day)	<76000	<36000	<20000
Conversion freshwater/seawater	10-25%	23-33%	20-50%
Reliability	Very high	Very high	Moderate for seawater
Maintenance (cleaning per year)	1-2	1-2	Several times
Pre-treatment of water	Simple	Simple	Demanding
Operation requirements	Simple	Simple	Demanding
Product water quality (ppm)	<10	<10	200-500

Reverse Osmosis technology is not the best option, according to the Greek Island Requirements. Mostly due to its maintenance, pre-treatment complexity and demanding operation. But most important, the water quality is higher in the thermal technologies. So, MSF and MED technologies are the option.

In thermal technologies, the performance ratio indicates the efficiency (mass of distillate produced/ mass of steam consumed). The best tactic to save energy in thermal desalination units is to use waste heat from the turbine to the condenser resulting in lower electrical consumption. Between the two dominating thermal desalination technologies, Multi-Stage Flash prevails in higher capacities since the various stages can combine into a single unit. For the same performance ratio with MED, it has this design advantage that eliminates external piping. Multi-Effect distillation is preferred for smaller facilities, consumes less power for pumps, and requires less heat exchange surface [54]. Also, it does not require high steam temperatures and pressures, helping prevent scaling as well. However, applying advanced pretreatment of the feedwater (chemical precipitation, ion exchange, electrocoagulation) lowers the risk of scaling, so that higher feed steam temperatures (120°C) are permitted [55]. But if the steam is heated at lower temperatures, the yield can be increased by 50% when the surface area is augmented by 30%, and the unit is then Low Temperature MED or LT-MED [16]. Initially, the combined unit is as in Figure 12, with different heat transfer fluid in the CSP unit and heat transfer to steam in 3 stages. Concentrated solar power technology is both producing power and providing thermal energy to the Low-Temperature Multi-Effect Distillation (LT-MED) unit through the steam. The characteristics of the combined plant are in the table below:

Table 22: Parameters of classic CSP-MED plant such as steam temperature for desalination(°C) and Heat transfer fluid [17], [55], [56]

Parameter	**Value**
Classic CSP-MED plant as in Figure 12 [17]	
Types of fluids	Separate closed circuit of CSP heat transfer fluid and steam for power production and thermal desalination
Superheated steam temperature that enters the turbine (°C)	380
Steam temperature after turbine for MED (°C)	135
Heat Transfer fluid	Oil (unknown type)
Differentiated LT-MED parameters	
Steam temperature after turbine for MED (°C) [55]	75
Differentiated CSP parameters	
Heat Transfer fluid is only one, Steam	The CSP is Directly generating steam to one closed circuit usually Linear Fresnel

The combined CSP-LT-MED unit consists of four parts:

1. LT-MED desalination block
2. Power generation block
3. Thermal storage block (optional), and
4. CSP block with separate closed circuits of fluids as in Figure 12

The combined unit is schematically according to the following flowsheet, includes thermal storage and fossil fuel back-up [54]:

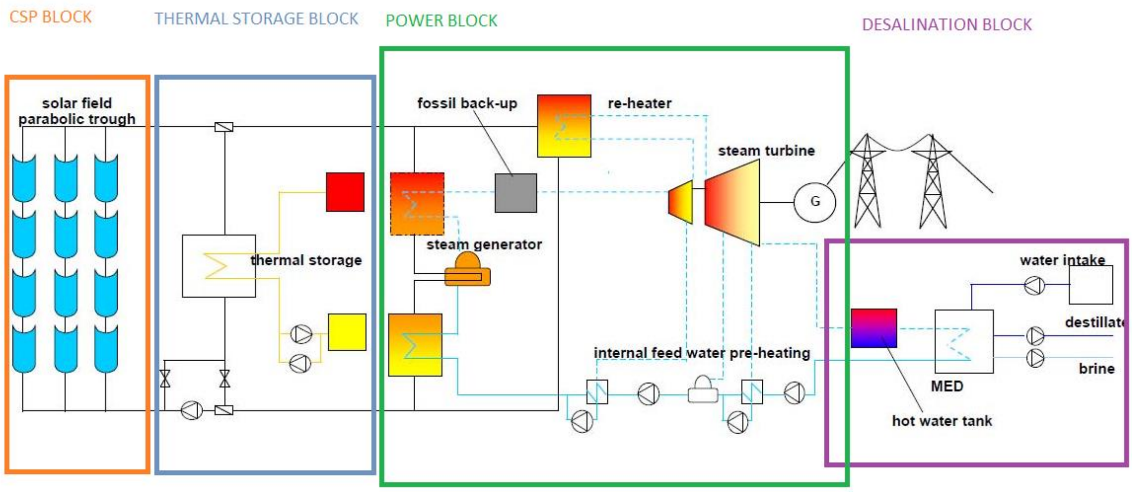


Figure 30: Flowsheet of combined CSP and LT-MED desalination unit with electricity production, thermal storage, and fossil fuel back-up [54]

The LT-MED desalination process is the optimum technology for this case. Its outstanding features are summarized [56]:

- As mentioned above, thanks to low operating temperature of steam entering the MED unit and the top brine temperature that can be below 75°C, there is low corrosion and scaling that allow the use of cost-friendly aluminum alloys. Also, reduced heat loss and minimal thermal insulation are possible thanks to the low temperature [56]
- Even though RO is also suitable for the Mediterranean waters, membrane lifetimes last for up to 5 years and demand expensive pre-treatment increasing costs, resulting in the choice of this LT-MED desalination technology [56]
- MED is the second most popular technology installed in Greece, and so it is tested and mature. LT-MED will be installed in small islands where the area is

limited, and since with only 30% more area needed, the outcome is increased by 50%, then it is preferred for this case [16].

The LT-MED flow diagram is shown in detail in the following figure. It includes the exact temperature and pressure of the steam exiting the power block of turbines. Also, the temperatures of saltwater, the brine, and the desalinated water. The flow rates vary, depending on the wanted capacity of freshwater, but all the rest remain the same [56]:

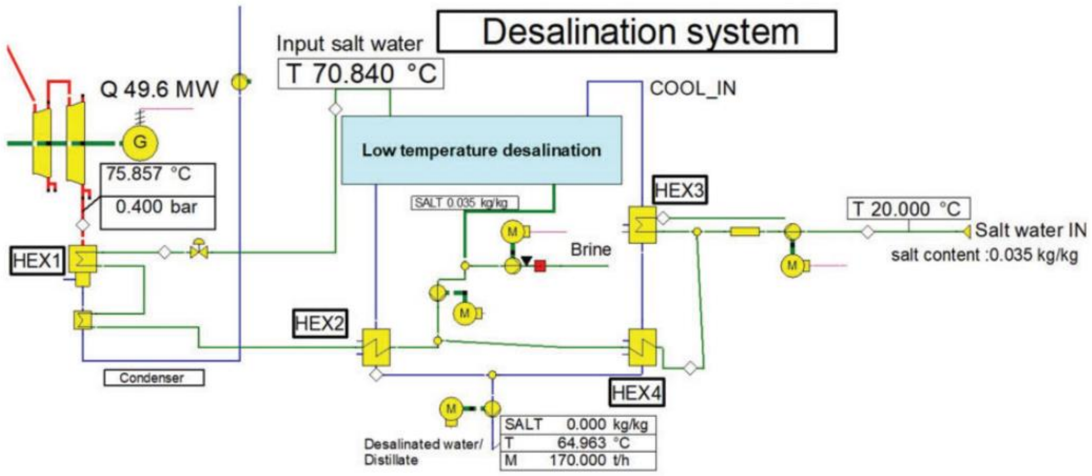


Figure 31: Flow diagram of the LT-MED desalination block, temperatures of each stream and HEX: Heat exchanger [56]

The CSP block may vary in the selection of both Line solar technologies, either Parabolic trough or Linear Fresnel, and of the Heat transfer fluid, as explained in Table 22. Depending on the CSP technology and if it is with indirect or direct steam generation differentiates, in turn, the thermal energy storage. It should be noted that the combination of thermal energy storage assists in keeping the feed water at a required temperature during days when the weather is not optimum for heat production. In that classical case, the Heat transfer fluid thermal oil, is directly stored in two storage tanks, one hot and one cold. The storage block is isolated. The oil has high stability compared with steam, making the application more secure at ambient pressures. The solar thermal energy is directly stored in the hot tank (384ºC) in the fluid, but when the fluid's temperature drops (~300ºC), it is stored in the cold tank. When needed, the cold thermal oil is pumped through the receiver and absorbs the thermal energy increasing its temperature [56]. During the detailed design, and simulation of the CSP unit, the thermal storage block will be re-examined and analyzed. It is certain, that the storage block will be included in the overall facility, to achieve the optimum continuous operation of the unit, and supply of freshwater.

For this research, the power block is not included. There is only interest in the thermal energy providing the desalination facility. Only if the thermal needs are covered, then there will also be power production. The Flowsheet of the combined facility is going to be like the one below:

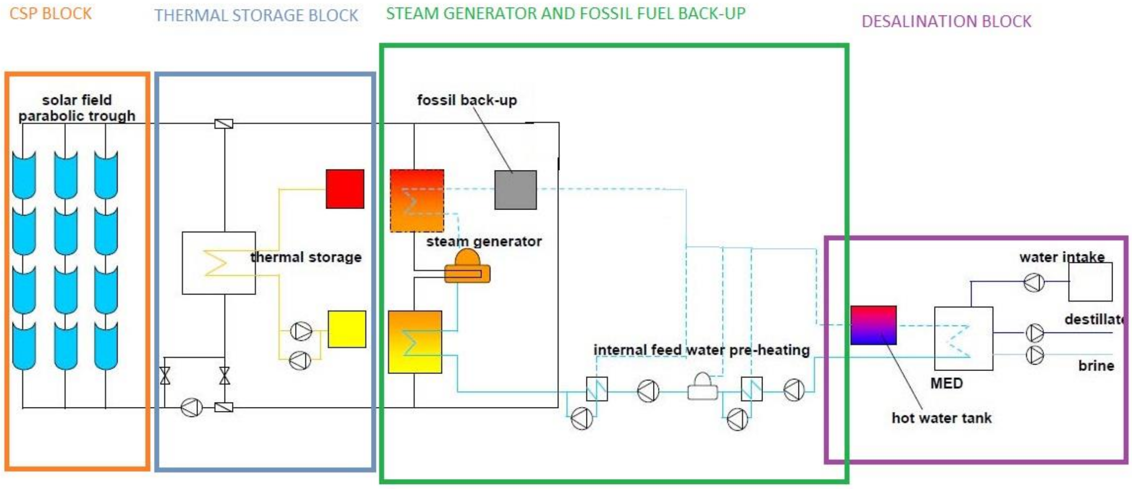


Figure 32: Flowsheet of combined CSP and LT-MED desalination unit with thermal storage, and fossil fuel back-up [54]

Concluding, in this flowsheet, the stages are:

- LT-MED desalination block
- Steam generation along with fossil fuel back-up
- Thermal storage block, and
- CSP block with specific oil as heat transfer fluid

4 Contribution

This chapter consists of two parts. The first is the energy consumption of the desalination unit in a Greek arid island, resulting from data found in literature. The second is the design of the solar thermal unit that will cover the energy needs of desalination.

4.1 Desalination unit energy configuration

The following paragraphs explain all parameters used to determine the Greek desalination unit and its energy consumption.

The methodology applied consists of logical steps that examine every parameter one after another. Only if the first parameter is defined and justified one proceeds to the next. The final parameter will be the choice of Concentrated Solar thermal technology. The design of the Solar thermal facility in the simulation program is the result of this methodology.

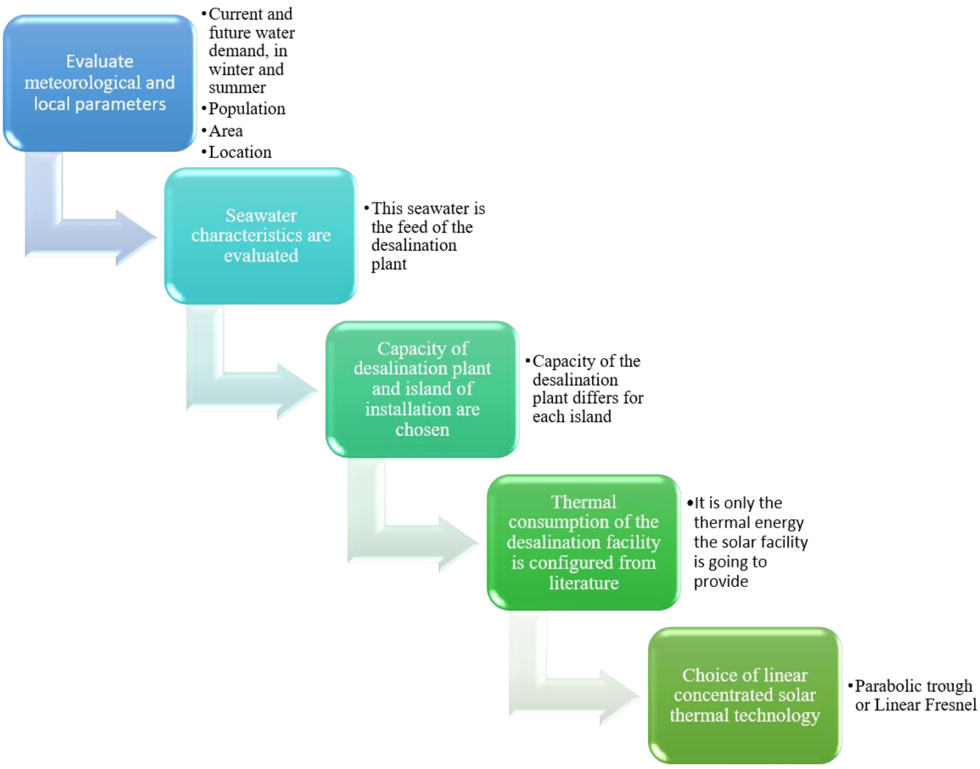


Figure 33: Methodology applied for the desalination and solar unit design.

4.1.1 Local parameters and demands

Local parameters along with winter and summer water demand will result in the desalination capacity per island. Exact location, total area, maximum elevation, mean annual precipitation, water quantity being transported from 2010 to 2014 are the characteristics needed. The following table summarizes them all [34]:

Table 23: Characteristics of the most arid Greek islands [34]

Island	Lat.	Lon.	Area (km^2)	Eleva-tion (m)	Popu-lation (2011)	Mean Precip-itation (mm/y)	Mean Annual Quantity of Water Transported (m^3/y)
Dodecanese complex							
Lipsi	37.301	26.681	15.84	277	790	576	49989
Chalki	36.222	27.602	26.99	593	478	889	40405
Megisti	36.150	29.584	9.11	273	492	858	27624
Cyclades complex							
Kimolos	36.793	24.556	37.43	364	910	439	49713
Heraclea	36.845	25.378	18.08	419	141	445	16457
Schinoussa	36.871	25.506	8.14	133	227	448	25692
Koufonisi	36.934	25.570	5.77	107	391	452	52333
Donousa	37.100	25.786	13.65	385	167	483	11640

From the data provided in Table 23, the island must have enough area. The desalination and solar thermal unit installed will cover the water need of both locals and tourists. This need results from both population and water transported annually.

For the winter season, which lasts from November to March, what interests is the water demand of the locals. The average daily consumption for Greeks for the past four years is $0.29m^3$/cap/day[57]. The desalination plant capacity for each island for the winter season is in Table 24:

Table 24: Desalination plant winter capacity (m^3/day) for each island

Island	Population	Winter capacity (m^3/day)	Winter total (m^3)
Lipsi	790	231	34,721
Chalki	478	140	21,008
Megisti	492	144	21,623
Kimolos	910	267	39,995
Heraclea	141	41	6,197
Schinoussa	227	67	9,977
Koufonisi	391	115	17,184
Donousa	167	49	7,340

The total water needed for winter months, and the average water quantity transported annually are used to calculate the average excess need for the summer months. The number of visitors and tourists for each island is distributed in the summer months from 5% to 30% of their total [34]. The same is assumed for the total water need during summer period. The following table shows all the needed amounts and results in the summer capacity of the desalination facility:

Table 25: Desalination plant summer capacity (m^3/day) for each island

Island	**[a] Winter total (m^3)**	**[b] Mean water transported (m^3/y)**	**[c] Extra total water in summer ([b]-[a]) (m^3)**	**[d]Distributed 30% of [c] (m^3)**	**Summer desalination capacity (m^3/day) (winter capacity+[d]/30)**
Lipsi	34,721	49,989	15,269	4,581	384
Chalki	21,008	40,405	19,397	5,819	334
Megisti	21,623	27,624	6,001	1,800	204
Kimolos	39,995	49,713	9,719	2,916	364
Heraclea	6,197	16,457	10,260	3,078	144
Schinoussa	9,977	25,692	15,715	4,715	224
Koufonisi	17,184	52,333	35,149	10,545	466
Donousa	7,340	11,640	4,300	1,290	92

The final capacity for the solar thermal facility design is according to the winter one because, during summer, the irradiation is much higher and will cover the daily needs. The irradiation on the island is one crucial characteristic. So, for all the islands of interest, their solar irradiation data are downloaded from the Global Solar Atlas website and are gathered in the following table [58]:

Table 26: Solar Irradiation Data for the islands of study [58]

Island	**Direct normal irr.**	**Global horizontal irr.**	**Diffuse horizontal irr.**	**Global tilted irr. at optimum angle**	**Annual Air Temp.**	**Terrain elevation**
	DNI	GHI	DIF	GTI_opta	TEMP	ELE
Unit	kWh/m²	kWh/m²	kWh/m²	kWh/m²	°C	m
Kimolos	1781	1793	625	1989	18.2	82
Heraclea	1918	1841	629	2060	17.9	91
Schinoussa	1924	1838	627	2050	18.3	27
Koufonisi	1926	1835	628	2053	17.9	71
Donousa	1908	1828	625	2036	18	45
Lipsi	1950	1847	614	2062	18.5	17
Chalki	1868	1855	651	2057	18	276
Megisti	2019	1903	638	2146	20	97

4.1.2 Feedwater characteristics

The characteristics that mostly concern are salinity and temperature. From the following figure, the depth of water is crucial. In intermediate depths, 200-400m, salinity and temperature fluctuate because of the living species [59]. Seawater pumping is from the depths of 60m maximum in a way that does not affect the local environment, designed as a seabed filter intake through directed drilled horizontal drains [60],[53],[61]. The salinity and temperature are 38,468mg/l TDS and 20°C, respectively.

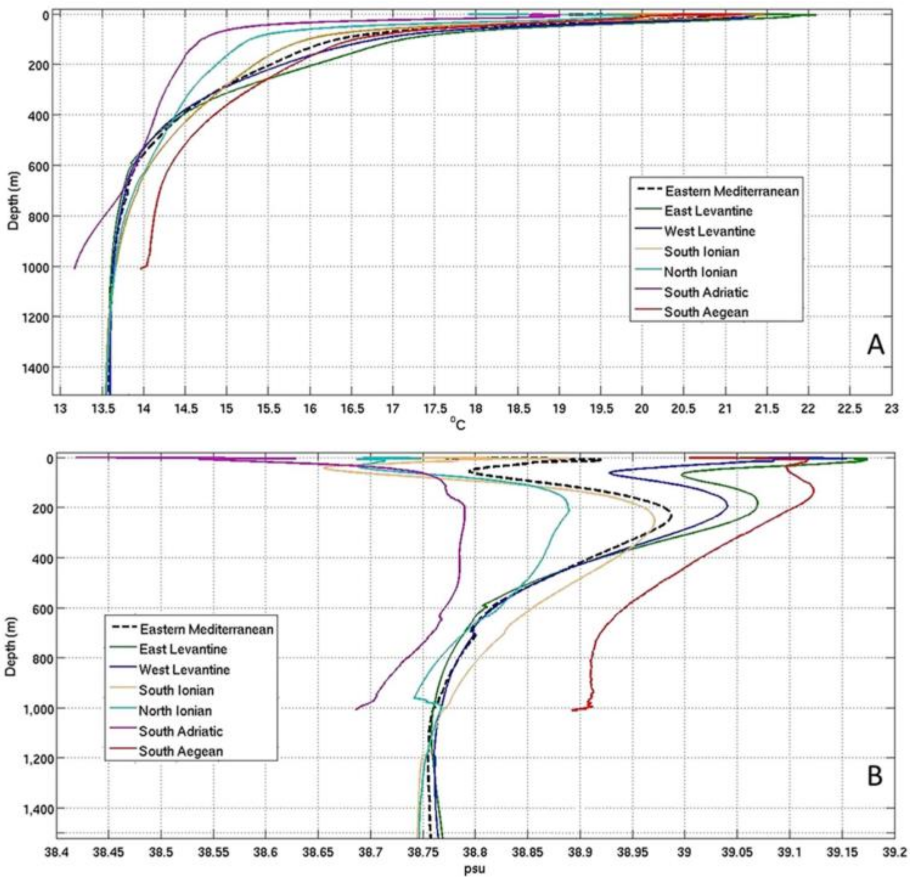


Figure 34: Average profiles of potential temperature (A) and salinity (B) per examined region for the 14-year period (2004–2017) [59]

Also, from oceanographic data in several stations in the Aegean Sea it is evident that the water contains Dissolved Oxygen, Nitrogen, Phosphorus, Silicate, and Chlorophyllia [62]. Apart from that, seawater has an ionic composition, as shown in Table 7. Pretreatment of water is only going to leave Cations (Na^+, K^+, Ca^+, Mg^+) and Anions (Cl^- ,SO_4^{2-},NO_3^-,HCO_3^-) [55]. The total salinity, though, must be the same as in the beginning. So, the feed water will have the following ionic composition:

Table 27: Final seawater ionic composition of the feedwater

Constituent	Final composition feedwater
Chloride (Cl^{-1})	21,326.5
Sodium (Na^{+1})	14,185.5
Sulfate (SO_4^{-2})	2,972.2
Magnesium(Mg^{+2})	1,403
Calcium (Ca^{+2})	424.6
Potassium (K^{+1})	463.2
Total Dissolved Solids (mg/l)	38,468

4.1.3 Island selection

The morphology of the island should be suitable for the installation of both the solar thermal unit and the desalination plant. The installment should also be away from the settlements. Kimolos island may have a wider surface compared with the other islands, but is within the Aegean volcanic arc and consists mainly of acidic volcanic rocks [63]. There was a desalination facility with geothermal energy on this island, but Kimolos is not the most competitive for the facility studied in the present document. Its geothermal dynamic should exploit, but that is not of any concern for this work. The rocky terrain for a solar thermal unit is an obstacle. The following set of images are all the islands of interest acquired from the Geodata governmental website, where all the settlements appear with light green dots, and wildlife sanctuaries appear with a yellow net. Also, the road network is displayed [32]:

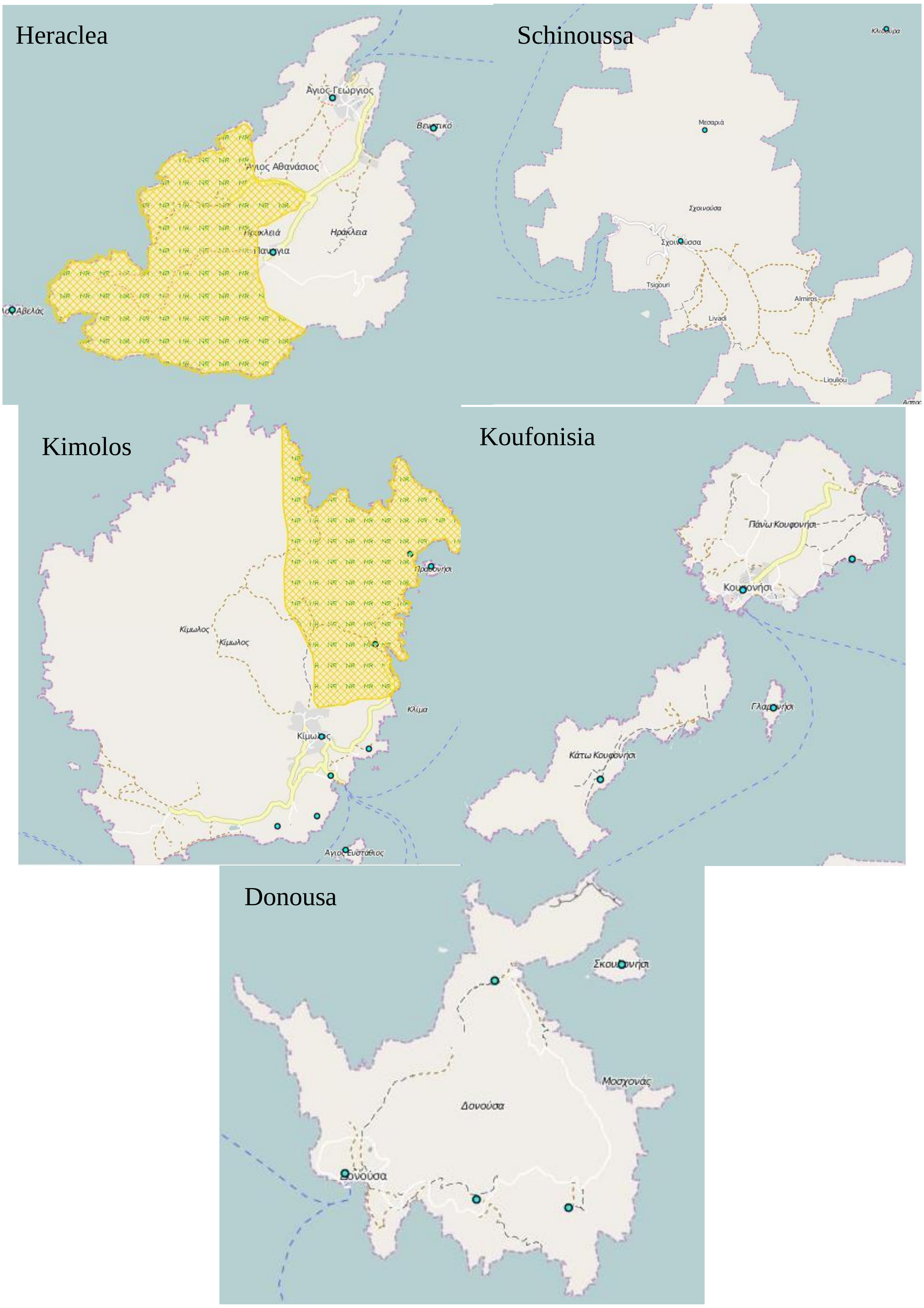


Figure 35a: Arid islands in Cyclades complex [32]

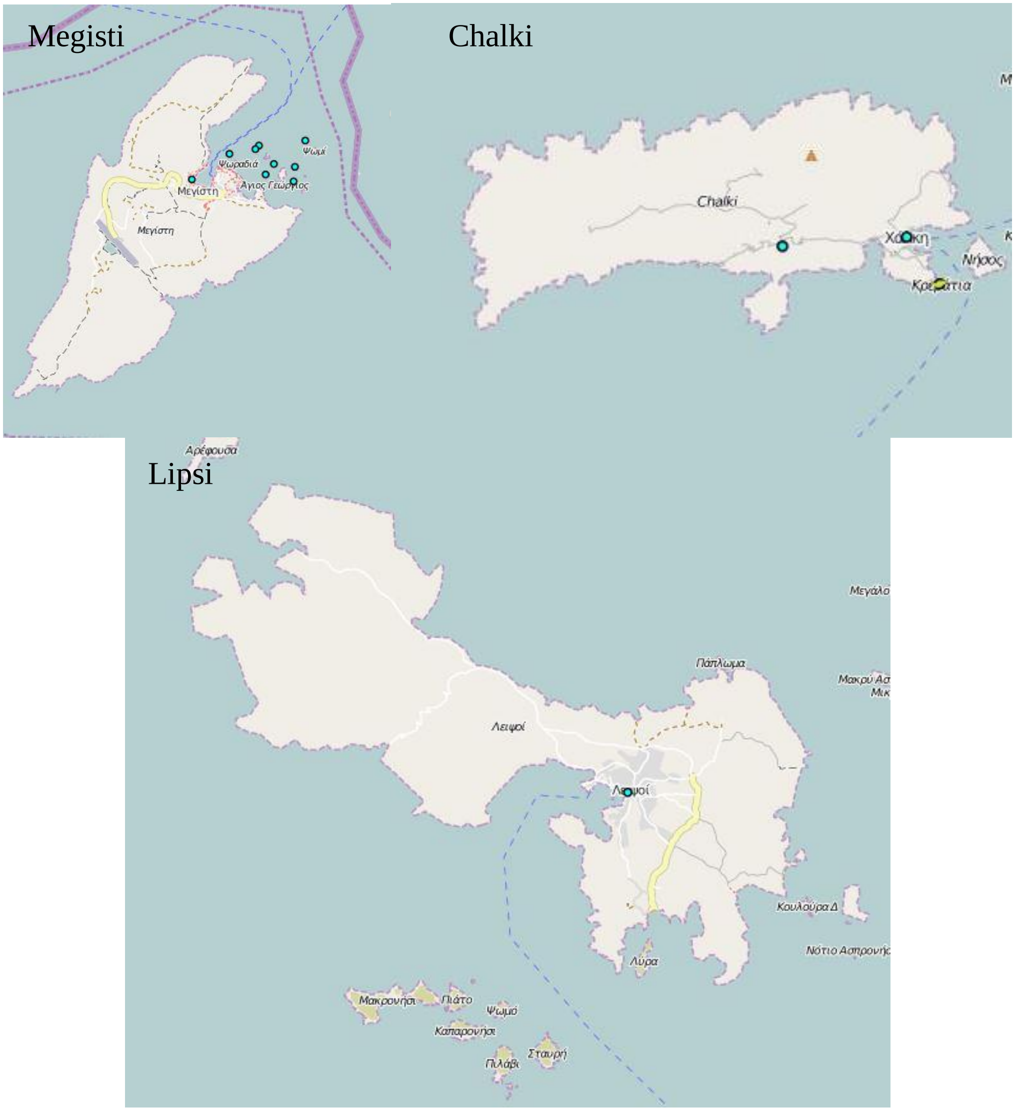


Figure 36b: Arid islands in Dodecanese complex [32]

From these figures, one would conclude that in the Cyclades complex, the island of Heraclea also consists of a long land that is a wildlife sanctuary, and like Schinoussa, Donousa, and Koufonisia, it is small. In the Dodecanese complex, even though that the island of Chalki is bigger than the others, it consists of a lot of small mountains and is barren. Only in the middle has a few plains that have the use of agriculture [64]. Lipsi island on the other hand, even though it has not enough area to exploit, its territory is mostly low hills and small valleys [64]. The settlements are on the south, so Lipsi is an ideal choice.

Regarding the Direct Normal Irradiance, even though Megisti island has the higher one, its location is not strategic as it is remote and small. It is of historical significance, so it would not be wise to choose it for a solar thermal desalination plant. Lipsi is the next better choice since it has the higher Direct Normal Irradiance 1950kWh/m^2.

4.1.4 Thermal Energy Consumption

The energy consumption of concern is the thermal one, which is provided by the concentrated solar facility. The thermal demand range of Multi-Effect Distillation is compared with other type of desalination plants in the following table [65]:

Table 28: Overview of energy requirements for different desalination techniques [65]

	Electrical Energy [kWh/m³]	**Thermal Energy [kWh/m³]**
Multi-Stage Flash (MSF)	4-6	53-108
Multi-Effect Distillation (MED)	1.5-2.5	64-108
Multiple-Effect Distillation with Thermal Vapor Compression (MED-TVC)	1.5-2.5	40-108
Reverse Osmosis (RO)	3-5.5	

For a more specific thermal demand in this study, the value is 80kWh/m^3 desalinated water, and by several studies, it ranges between 71.8 and 85kWh/m^3 [65],[66],[67],[68]. The product water capacity is 230m^3/day, leading to an optimal need of 18,400kWh/day or 18.4MWh/day to be covered by the solar thermal facility during the winter season. During the summer season the capacity should be 384 m^3/day, leading to an optimal need of 30,720kWh/day or 30.7MWh/day to be covered by the solar thermal facility. Concluding the minimum thermal production in a year that is needed from the desalination facility is 6,716MWh/year. The exact parameters to be used in System Advisor Model analyze in a different paragraph.

4.1.5 Choice of concentrated solar technology

The solar thermal facility is going to be with concentrating parabolic troughs. It is the most used for CSP and a reliable technology. For practical reasons, the Linear Fresnel collector requires a 33% more mirror aperture area than parabolic troughs. In other cases, it can easily integrate into industrial or agricultural areas, and especially in deserts, its shade is valuable [53]. But, for Greek islands it is wiser to use parabolic troughs.

The Desalination unit is a Thermal Low-Temperature Multi-Effect Distillation one, with a capacity of 230m^3/day. The land area is including excess space according to the summer desalination capacity (average land area 1200m^2 per 1000m^3/day [4]). The specifications of the unit also summarize in the table below:

Table 29:Specifications of the solar thermal driven LT-MED plant

Parameter	Value
LT-MED chamber	
Sea water temperature in system (°C)	20
Sea water temperature in system in first effect (°C)	70
Sea water salinity TDS (mg/l)	38,468
Feed steam temperature in first effect (°C)	73
Feed steam pressure in first effect (bar)	0.35
Desalinated water temperature (°C)	65
Brine disposal temperature (°C)	38
Brine disposal salinity TDS (mg/l)	63,000
Specific thermal power demand (kWh/m^3)	80
Productivity (m^3/day)	230
Product water quality (ppm)	<10
Land area (km^2)	0.0046 [4]
Daily Hours of operation (h)	12

4.2 Solar thermal facility design

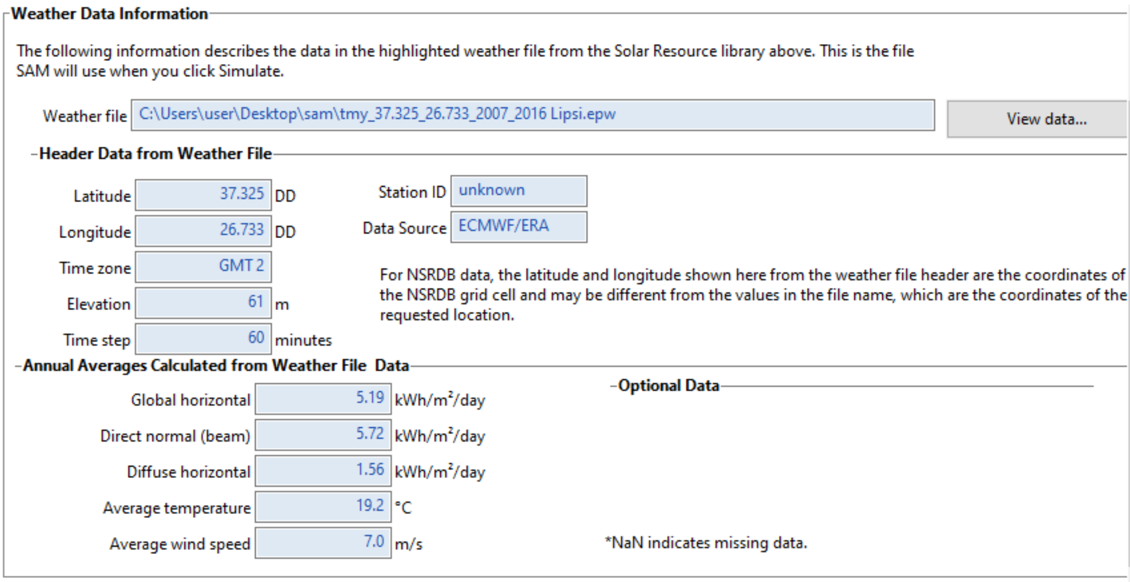
This paragraph consists of two sub-paragraphs. The first one explains all the parameters set in the System Advisor Model (SAM), one after another. The second analyzes all the results of one simulation.

The System Advisor Model is a performance and financial model designed by the National Renewable Energy Laboratory of the U.S. Department of Energy. It is for all people working in the renewable energy industry and is a tool that aims to assist project managers, engineers, policy analysts, technology developers, researchers and everyone involved. It can predict the performance of all types of renewable energy models , as well as estimate energy costs and cost indicators of projects. It is a valuable tool for the customer, retail, utility services and selling electricity through a power purchase agreement. The SAM is continuously updated, renewed and free of charge. The databases include all components for all performance simulations of photovoltaic, concentrating solar power, solar water heating, wind, geothermal, and biomass power systems. Finally, it includes a basic generic model for comparisons with conventional or other types of projects [69],[70],[71].

4.2.1 System Advisor Model parameters

The System Advisor Model's first project is Concentrating Solar Power with Industrial Process Heat Parabolic Trough performance model. In it, heat from the solar field is for a thermal application and not electricity generation. In simple words, the power cycle is not part of this model and is not needed here. The parameters that can significantly change the result of the solar field and its sizing are Solar Multiple, Thermal Storage, and these affect the Capacity Factor that should maximize without neglecting the Levelized Cost that should also be as low as possible.

The first parameter to be set is the Location and weather file. For the island of Lipsi, all these data are acquired from the Photovoltaic Geographical Information System of the European Commission, specifically as selected in the map [72]. The typical meteorological year is for the period of 2007 up to 2016, and the basic annual average and data appear in the following picture:



Picture 1: Header Data and Annual Averages calculated from Weather File Data in SAM first project simulation.

The System Design requires solar field parameters. The first is the reference Direct Normal Irradiance (DNI), the greater it is the smaller the solar field area, so, fewer heliostats are needed to achieve the reference condition power. It represents the maximum actual DNI on the field expected for the location at which the plant should achieve the specified thermal rating, including thermal and piping losses. But neither a too high value is good nor a too low. For Line collectors (parabolic trough and linear Fresnel), the direct solar radiation rarely strikes the collector aperture at a normal angle due to the rotation on a single axis, meaning that the DNI incident on the solar field in any given hour will always be less than the DNI value in the resource data for that hour. The cosine adjusted DNI value that SAM reports in simulation results is a measure of the incident DNI [70]. So, at first, the value to be set is from the data in Table 26 that equals 1950W/m^2 and after specifying the storage capacity the simulation is run. When checking the statistics on the results, the maximum value of "Field collector DNI-cosine product (W/m^2)" is going to be the final reference value for every other simulation [70]. This value equals 912.582W/m^2 and for every other simulation the reference value set is 915W/m^2.

The next parameters are Heat sink power, Target solar multiple, and Target receiver thermal power. They are dependent on each other, according to Equation 1:

$$\textit{Receiver Thermal Power (MWt)} = \textit{Solar Multiple} \times \textit{Heat Sink Power (MWt)}$$

Equation 1

All these will determine the thermal energy delivered by the solar field under design conditions at the actual solar multiple.

The solar multiple represents the solar field aperture area as a multiple of the solar thermal rated capacity (Heat Sink Power). Increasing the solar multiple (SM>1) results in a solar field that operates at its design point for more hours of the year and produces more thermal power. The optimum value should balance both a larger solar field that maximizes the system's output and project revenue, and a smaller one that minimizes installation and operating costs. This value can be used to oversize the receiver design output relative to the heat sink and chosen equal with 1.7.

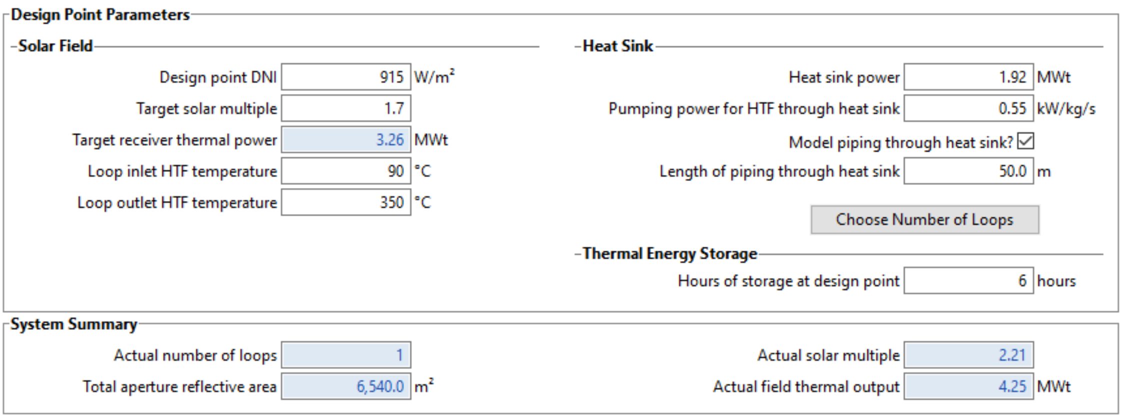
The Heat sink power value is going to be determined initially according to the capacity factor (CF) equation. When knowing the thermal power produced annually 6,716 MWh/year as described in Paragraph 4.1.4 then that is divided by the product of nominal capacity of the plant or Heat sink power (MW) multiplied by 8,760h/year, then the capacity factor is calculated from Equation 2 [56]:

$$\textit{CF=Annual Thermal Production (MWh/year)/Heat Sink Power (MW)*8,760 (h/year)}$$

Equation 2

The capacity factor for a CSP Parabolic Trough facility and 6 hours Thermal storage is between 40 and 53% [73]. So, assuming a CF=0.4 the Heat Sink Power is equal to 1.92MWt and when multiplied by solar multiple, results in a target receiver thermal power of 3.26MWt of the solar thermal facility. Also, piping through the heat sink is preferred in order to take advantage of additional thermal capacitance, avoid thermal losses, and pressure drop across the solar-to-process heat exchanger [74].

The heat transfer fluid (HTF) loop inlet and outlet temperature should be in the range of its minimum and maximum operating temperature. Thermal storage is added to the system as it changes the optimal solar multiple and increases the amount of time that the thermal block operates at its rated capacity. The hours of thermal storage at the design point are, as in the program's default of 6hours. Thermal storage is, for now, the classic one with two tanks, one hot and one cold, as described in Paragraph 3.4. The system design is complete and is, as shown in Picture 2:



Picture 2: Design point parameters in SAM first project simulation.

The Solar Field parameters and the Heat transfer fluid (HTF) selected are crucial because they affect heat loss, thermal inertia and capacity, and pumping power [75]. In this category, what can change is the solar collector assembly (SCA) type and the heat transfer fluid, as well as the single loop configuration. Initially, the HTF selected is Therminol VP-1 [56], and the single loop configuration consists of eight assemblies instead of four [76].

Row spacing, is the distance in meters between rows and collectors from centerline-to-centerline, assuming that rows are laid out uniformly throughout the solar field, and the default value is 15 meters [70]. This value should be equal to the chosen collector's aperture width multiplied by three times to avoid shadowing [77].

The number of field subsections determine the location and shape of header piping. It delivers HTF to the power block and affects the heat loss calculation. In this case, there will be two subsections to minimize pumping pressure losses [76]. The field formation is going to be as in the following figure:

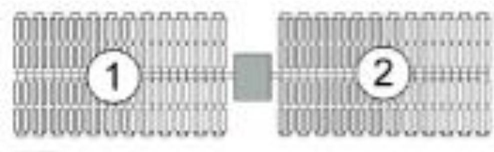
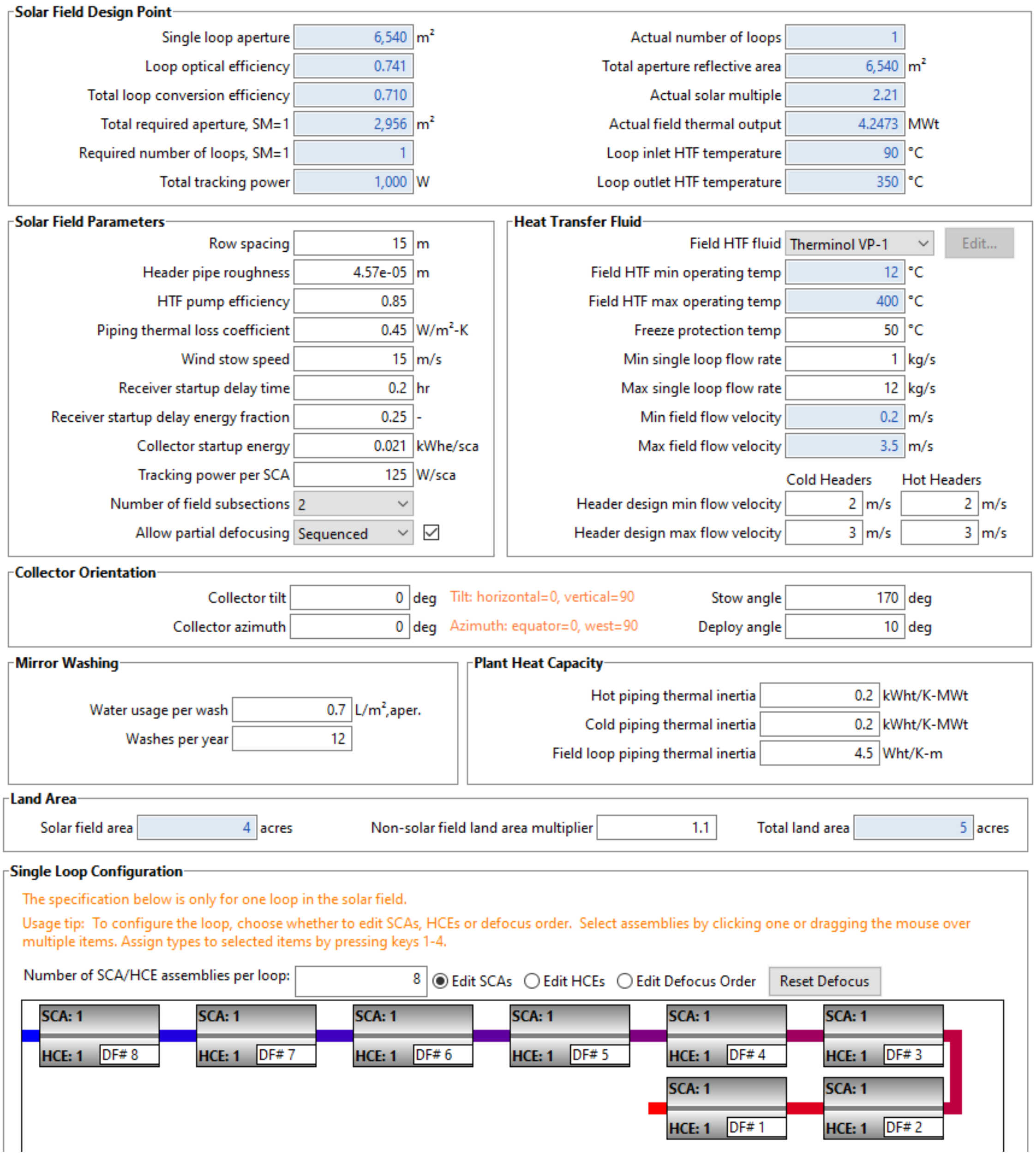


Figure 37: Field formation when there are only two subsections [70]

When the current wind speed equals the stow speed or is higher, the collectors in the field defocus and move to a safe position to avoid damage. In that case the field thermal power incident goes to zero. If not, it returns to normal. That is equal to 15m/s since it can have high winds on islands. Header pipe roughness, HTF pump efficiency, Piping thermal loss coefficient, Receiver startup delay energy fraction, Collector startup energy and Tracking power per SCA are left in default values as seen also in bibliography[76],[71]. Freeze protection temperature is better to be much higher than the Field HTF min operating temperature but also lower than the Loop Inlet HTF Temperature, and it is equal with 50^oC.

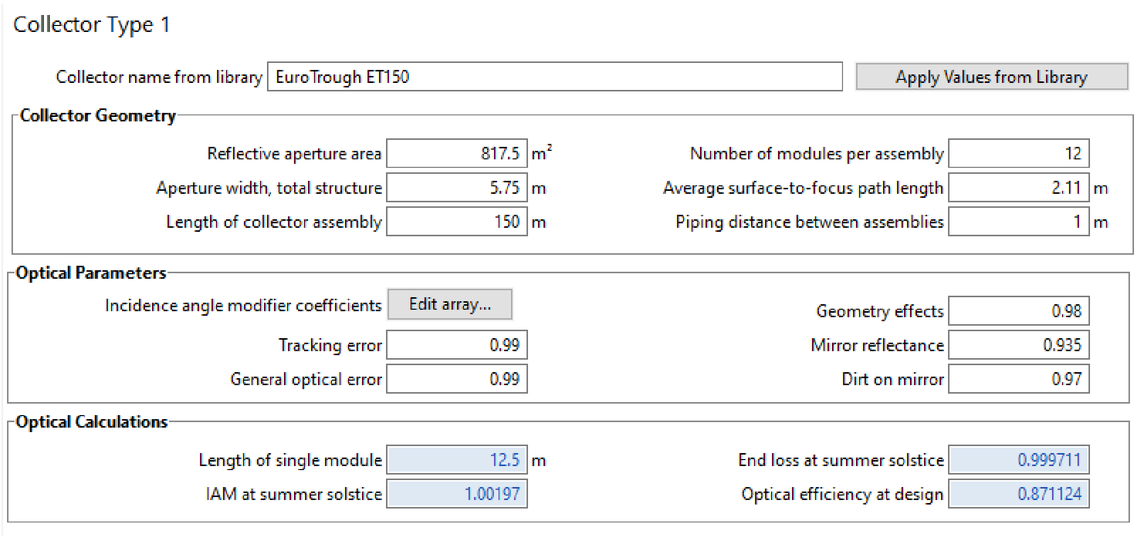
Stow and deploy angle are the same as in the bibliography [76].

Finally, for this section, mirror-washing should be done twelve times because the cleaner the troughs' surface is, the better the efficiency [78].



Picture 3: Solar field parameters in SAM first project simulation.

Collectors chosen for this first simulation are the Eurotrough ET150. They were used in the ANDASOL 1 plant in Spain successfully [79]. They are European and have similar characteristics as the also European Albiasa Trough. The total aperture area required from the System Design is 13,080m^2. Some technicalities of these collectors are in the Appendix: ”Eurotrough Collectors***[92]***”. The Eurotrough ET150 has the following geometry and optical parameters:



Picture 4: Characteristics of Eurotrough ET150 Collector

The Reflective aperture area of the Solar Collector Assembly (SCA) equals 817.5m^2. The Solar Collector Modules (SCM) have an aperture width of 5.75m since the number of modules per assembly equals 12. Then their reflective aperture area equals 817.5m^2/12=68.13m^2. Since the length of the assembly is 150m, each module's length is 150m/12=12.5m. But that, of course, can be modified to save land space. What cannot be changed is the reflective aperture area of the SCA. Each loop consists of 8 SCAs as the total aperture area of the loop equals A_{loop}=817.5m^2*8=6,540 m^2, and the complete unit requires only one loop to complete the aperture area.

The receivers are some of the most complex parts of the Parabolic trough assembly. The receiver heats up and a significant portion of heat is transferred to the HTF that circulates within. The receiver unit consists of a steel absorber tube that is inside a glass envelope. The tube is sealed with a specific glass to metal seal and ends up on both sides to expansion bellows. In those parts, the Heat collector element length to avoid the heat conduction at the ends. The annulus between the transparent glass cylindrical envelope and the absorber tube, where the HTF flows, must be evacuated to prevent heat conduction or convection because the two parts have a temperature difference. The air is evacuated through a glass pin. The absorber is coated with a selective surface of high solar absorption (>0.95) and low thermal emittance. Finally, the diameter of the absorber tube, is also reduced but dependent on the collecting aperture of the reflector [76],[80]. A figure below is assisting in the understanding of the structure [80]:

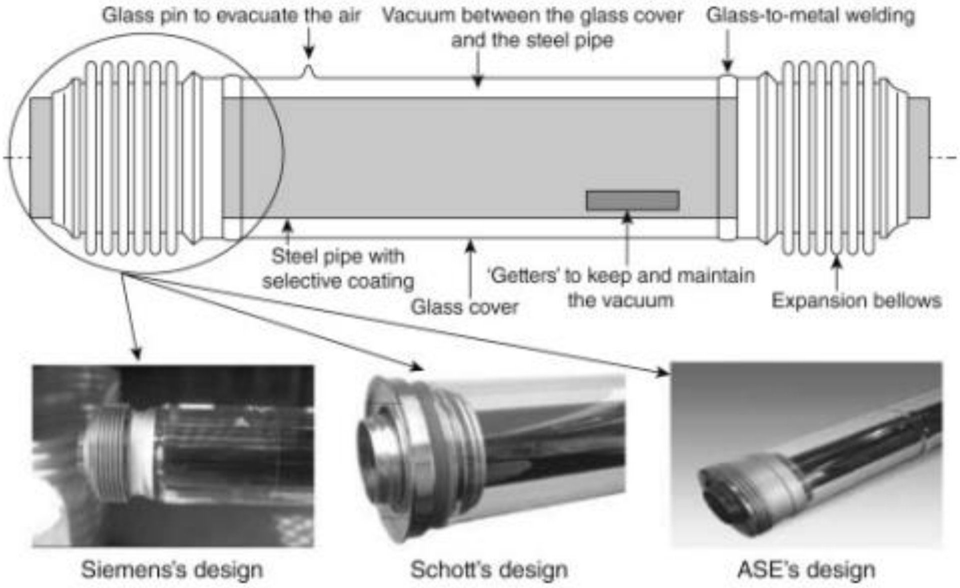
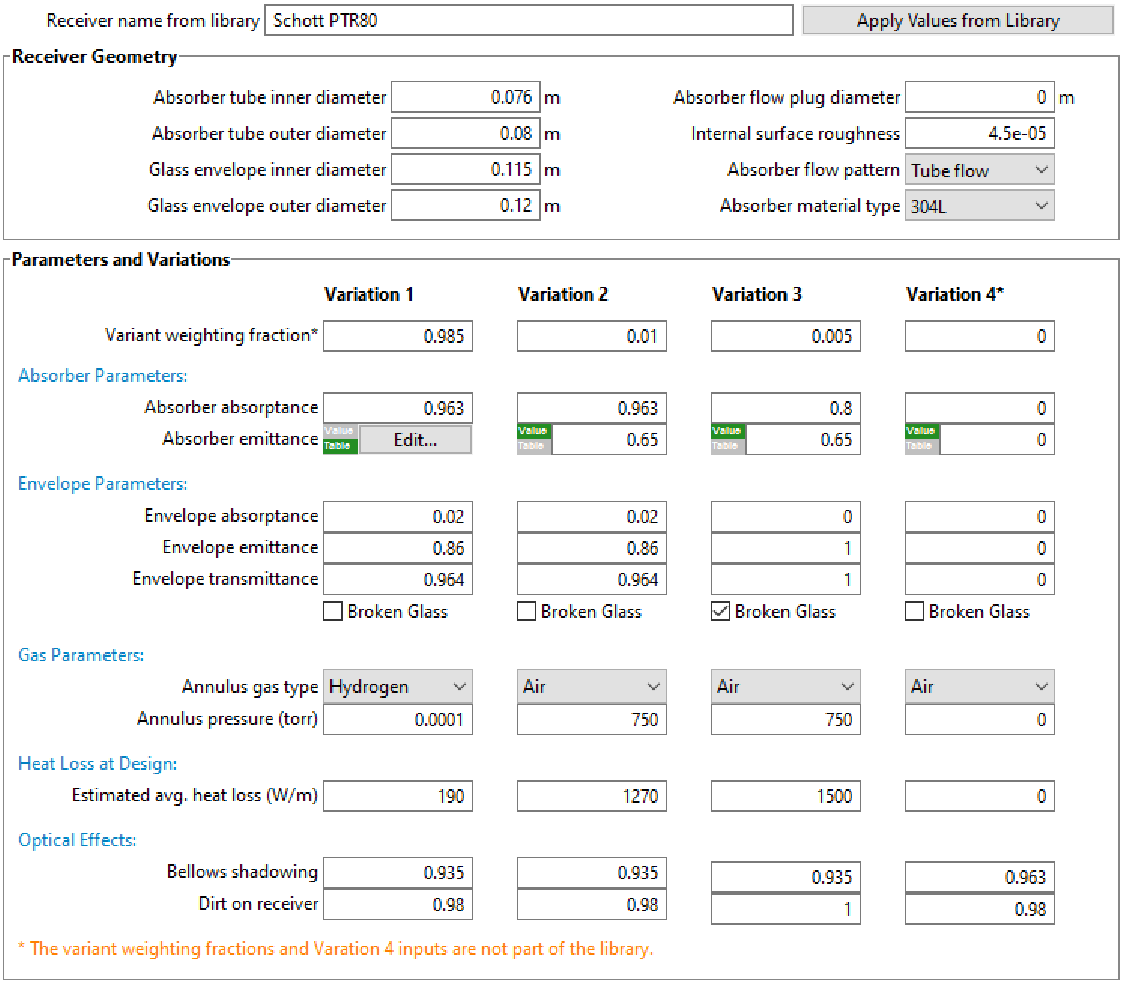


Figure 38: Structure of the parabolic trough receiver [80]

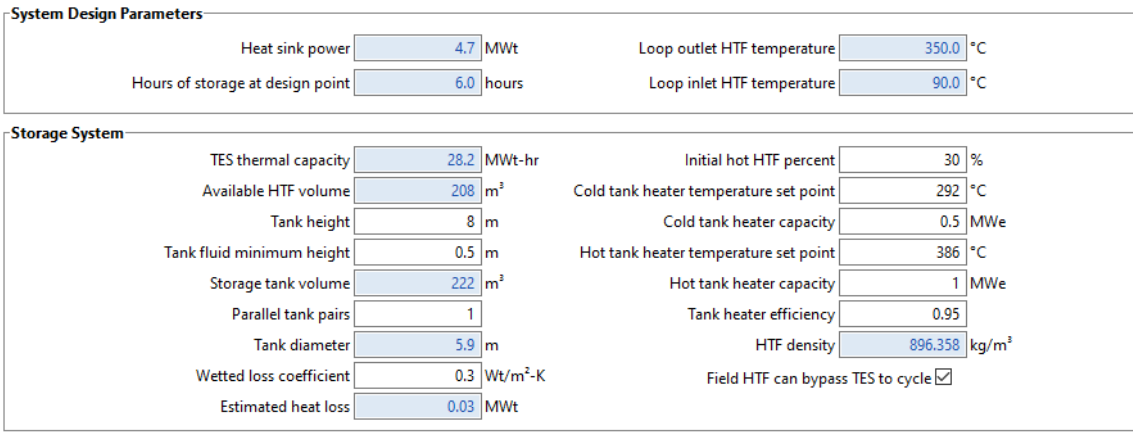
The receiver chosen is «Schott PTR80», one of the most reliable, and as seen in bibliography [79], [76], [81]. The situation of the receiver depends on the Absorber, Envelope and Gas parameters. These represent the receiver's degradation through the years. Part of their thermal insulation is lost, or there is a breakage of the glass tube. Heat loss is the result of all this. There is considered that 98.5%of the receivers is in good condition and so, Variation 1 has a variant weighting fraction 0.985, the rest 1% is degraded (Variation 2 fraction=0.01), while only 0.5% is broken (Variation 3 fraction=0.005) [82]. In the case the receiver is in good condition, the thermal decomposition of the organic heat transfer fluids may lead to permeation of Hydrogen into the annular region leading to more heat losses. Even though the pressure is very low, this Hydrogen must later be removed, with expensive chemicals and tools. As for the degraded and broken receiver there is air permeation in ambient pressure [82]. The heat loss would be devastating if there were a higher fraction of these two states in the whole solar field. The following picture depicts the receiver setting:



Picture 5: Receiver Schott PTR80 characteristics and setting in SAM first simulation

The total loop efficiency, $n_{loop,tot}$, is equal with the product of the collector's optical efficiency (the equations for the calculation of the collectors' and receivers' optical efficiency are in the Appendix "Optical parameters of collectors and Total Weighted losses of receivers[69]"), receiver's optical derate, and absorptance, that is 0.871124*0.850117*0.963=0.71 as it is already calculated in the Solar field design point [82]. According to the results, the total land area the solar field occupies is 4acres, as the total land area is 5acres or 0.0202km^2. The island has more than enough space.

Thermal Energy Storage (TES) consists of two tanks, one hot and one cold, with Terminol 1 as Heat transfer fluid. The parameters used here are from a CSP/RO plant designed like the Andasol 1 plant but with a smaller capacity, concluding in a tank height of 8m. Cold and Hot tank heater temperature setpoints are 292 and 386°C, respectively [79]. Tank heater efficiency is also 0.95 from the bibliography, instead of the 0.99 predefined from the program [79].



Picture 6: Thermal storage parameters [79]

System control determines the operating parameters of the system. Plant Energy Consumption has three parameters:

- Fraction of gross power, consumed at all times, is a fixed electric load applied to all hours of the simulation, expressed as a fraction of rated gross power, at design, from System Design parameters. This value is set as it is 0.0055MWe/MWtcap [70]. Equation 3 explains the fixed electric load Cfixed [75]:

$$\dot{W}\ fixed = Cfixed\ \dot{W}\ des$$

Equation 3

- Balance of plant-parasitic is the parameter for the losses as a fraction of the power block nameplate capacity, that apply in hours when the block operates [70]. Again, the Equation 4 is:

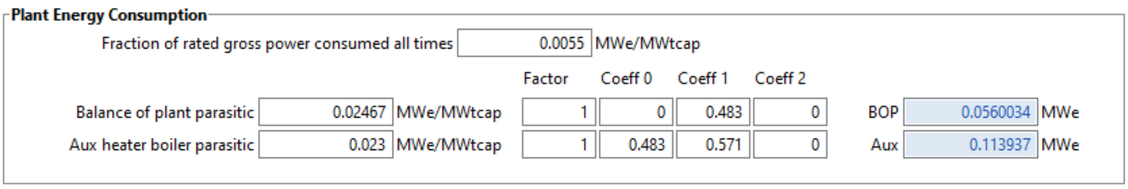
$$\dot{W}_{bal} = \dot{W}_{des}\, f_{bal}\, f_{adj} \left(C_{bal,0} + C_{bal,1} \frac{\dot{Q}}{\dot{Q}_{des}} + C_{bal,2} \left(\frac{\dot{Q}}{\dot{Q}_{des}} \right)^2 \right)$$

Equation 4

From pre-set values in SAM f_{adj}=1, $C_{bal,0}$=0, $C_{bal,1}$=0.483, $C_{bal,2}$=0. From bibliography [76] f_{bal}=0.02467MWe/MWtcap and the final result is calculated by SAM W_{bal}=0.056034MWe

- Auxiliary heater operation expresses the parasitic load from the fossil fuel back up heater. The equation it is based on is like equation 4. The value of f_{aux} is equal to 0.02273MWe/MWtcap as set in SAM and seen in bibliography [76]

System Availability losses are reductions in the system's output due to operational requirements such as maintenance downtime or other situations that prevent the designed operation. It is a 4% constant loss that applies to the system's entire output. Dispatch Optimization is an algorithm that determines the timing of energy delivery from the solar field to and from the thermal energy storage system. The algorithm defocuses heliostats in field to reduce the output power because excess thermal power is produced and is not required. No Dispatch optimization nor Control is needed [70].



Picture 7: Plant Energy Consumption setting

The method used to calculate the project's Levelized Cost Of Energy (LCOE) or Heat, in this case, is using only the following inputs [68],[69],[74]:

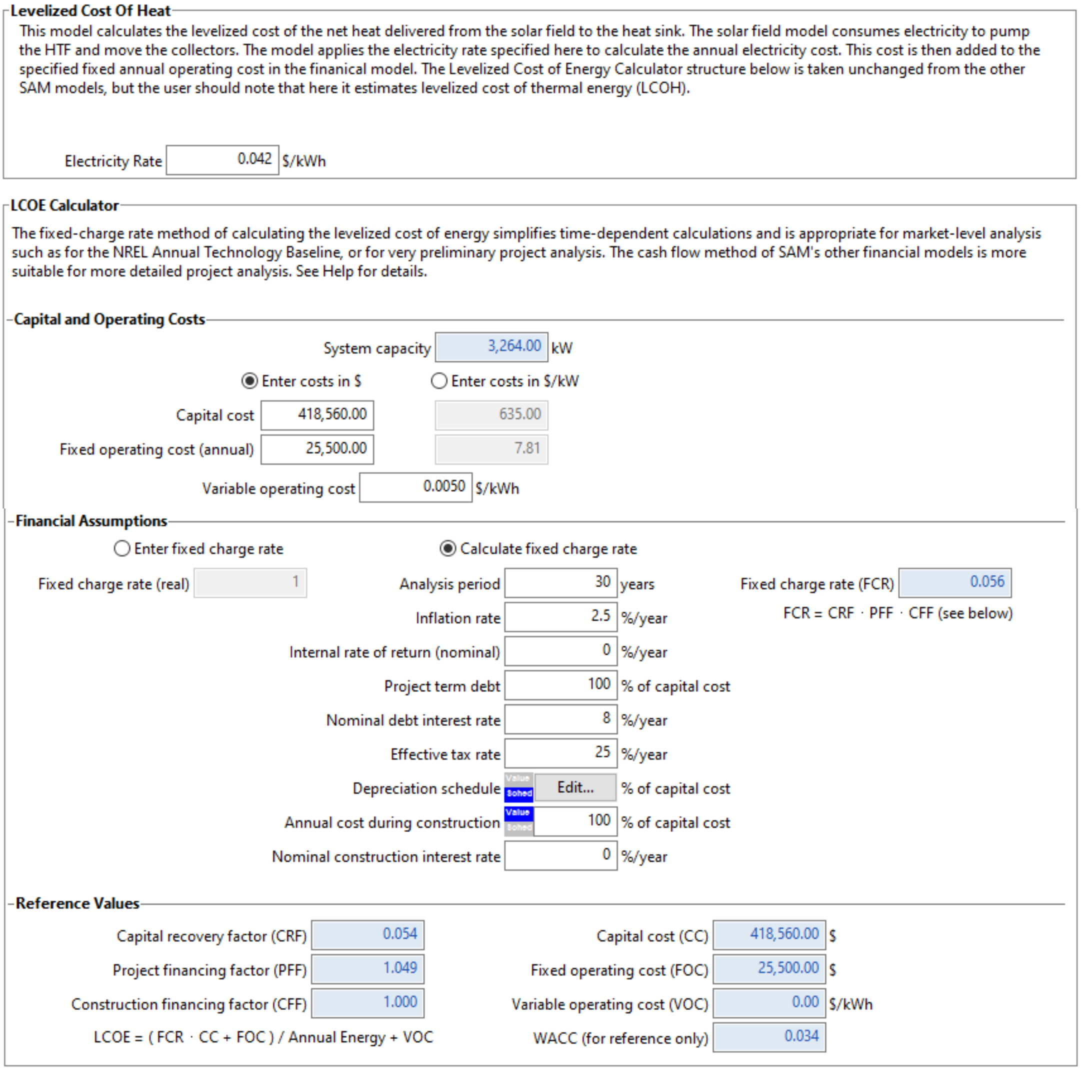
- Capital Cost, $ (TCC), or installed capital costs,
- Fixed annual operating cost, $ (FOC), or operations and maintenance costs,
- Variable operating cost, $/kWh (VOC), or operations and maintenance costs per unit of annual electricity production,
- Fixed charged rate (FCR) is the revenue per amount of investment required to cover the investment cost, and,
- Annual electricity production, kWh (AEP)

The equation to calculate the LCOE is:

$$\mathrm{LCOE} = \frac{\mathrm{FCR} \times \mathrm{TCC} + \mathrm{FOC}}{\mathrm{AEP}} + \mathrm{VOC} \qquad \text{Equation 5}$$

This method is more appropriate for very preliminary stages to evaluate the project's feasibility. For a more detailed analysis about a project's cost and financial costs, there are other methods.

Regarding the Levelized cost of heat (LCOH), the first price to be set is the electric energy current rate equal to 0.0417$/kWh [83]. Fixed operating and maintaining costs, and variable operating costs, for small scale CSP plants <10MW, are respectively 7.81$/kW/year and 0.0050$/kWh [78]. The Capital Cost is the total investment cost, depends on the solar thermal facility and the heat storage tank system. The cost of the storage tank system is approximately 20% of the total investment [84]. For a site land area of 50acres and desired thermal capacity of at least 10MW, the investment cost is 330$/m^{2}of reflective aperture area. Shipping cost is included [85]. Because the capacity of this thermal facility is 5.2 times lower, capital cost equals to 64$/m^2. For 6,540m^2 reflective area, that is 418,560$. The Analysis period is 30 years instead of 25, and the Nominal debt interest rate is 8%, as in the bibliography [84]. The Effective tax rate is equal to 24% as it is currently for Greece corporates [86]. Concluding, the Financial Parameters are as in the following picture:



Picture 8: Financial Parameters of SAM first simulation

4.2.2 System Advisor Model first simulation results

According to the parameters explained in the previous sub-paragraph, the main results of the simulation are as in Table 30:

Table 30: Summary of results of first simulation in SAM software

Metric	**Value**
Annual fixed operating cost ($/kW)	129,892
Annual Gross Thermal Energy Production w/ avail derate (kWt-hr)	7,631,984
Annual Net Thermal Energy Production w/ avail derate (kWt-hr)	5,077,402
Annual electricity consumption w/ avail derate (kWe-hr)	2.48553*10^6
Annual thermal freeze protection required (kWt-hr)	2.55458*10^6
Annual thermal power for TES freeze protection (kWt-hr)	2.55403*10^6
Annual thermal power for field freeze protection (kWt-hr)	547.87
Capacity factor (%)	30.18
First year kWh/kW (kWht/kWt)	2644.48
Levelized cost of energy ($/kWh)	0.03524
Total Annual Water Usage (m^3)	54,936

The capacity factor of the unit equals 30.18%, which is not content. The aim is for it to be closer to 0.4 or higher. During the winter months, the Heat sink Thermal power is inadequate and below the wanted 1.92MWt. For example, in Time Series, January is not covered, while month June is fully covered.

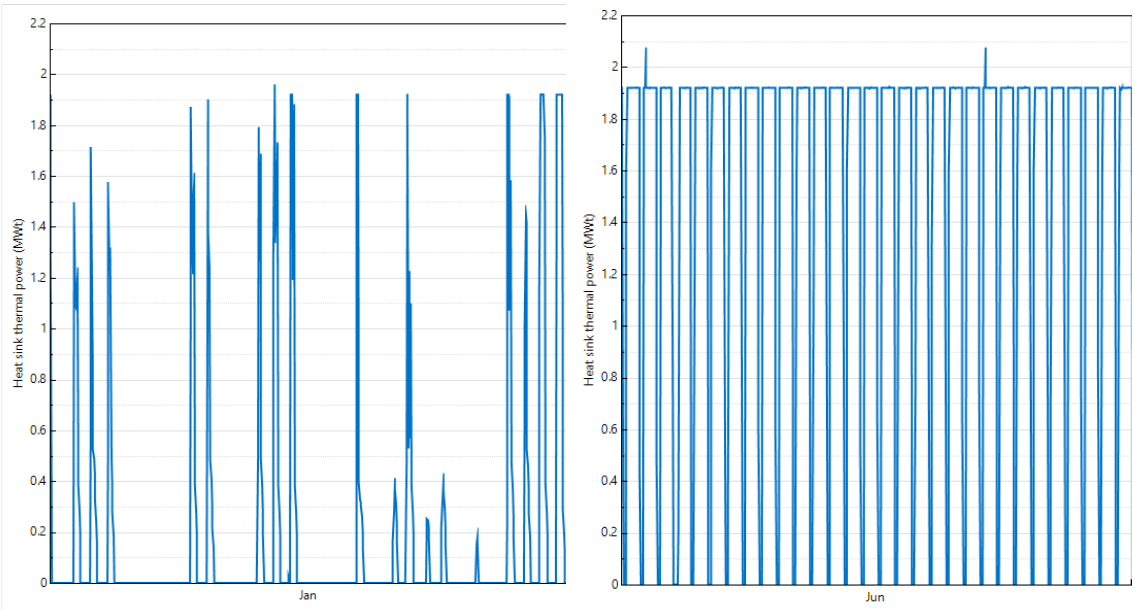


Figure 39: Heat sink thermal power Time Series for January and June

The worst months when no Solar thermal power is of use nor Thermal energy storage are January, November, and December. During the rest of the months, it is clear that TES Discharge thermal power covers the lack of Solar thermal power. It is during those months that the freeze protection is also in function. Obviously, for December, there is no thermal power to cover the desalination unit. That is an important issue that must be solved since it is not wise to use fossil fuel back up. The following heat map of the heat sink is also depicting this:

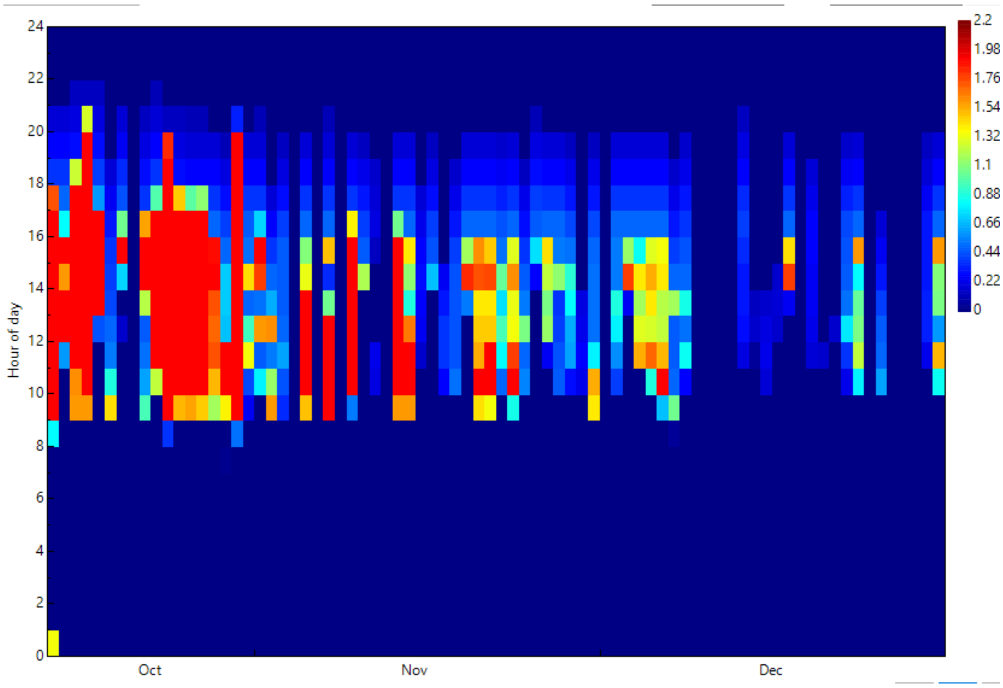


Figure 40: Heat map of Heat sink thermal power of first simulation.

4.3 Optimization of the Solar Thermal Unit

This paragraph is for the optimization of the existing facility. The parametrics that must be run are: Specific Solar multiple for values 1.7 to 5 with 1 step [87], Thermal storage hours from 6 to 8 with 1h step, Different Receiver from the library, and last but not least, different Heat transfer Fluid. The optimization of different heat transfer fluid such as pressurized water is analyzed in the end.

When the solar multiple changes, as the Heat Sink Power remains the same (2MW instead of 1.92 to be rounded), then for a solar multiple equal to 1.7 up to 2.1, the actual field thermal output remains the same. The Total aperture reflective area and actual number of loops are also unchangeable. From 2.2 to 4.2, they also have the same values but different from when the solar multiple is less than 2.2. The following table shows the change with the Solar Multiple values:

Table 31: Solar Multiple Values and results in Actual Field Thermal output.

Heat Sink Power	MW	2					
Solar Multiple		1.7	2.1	2.2	4.2	4.3	5
Actual Number of Loops		1		2		3	
Total aperture reflective area	m^2	6540		13040		19,620	
Actual Solar Multiple		2.12		4.25		6.37	
Actual Field thermal output	MW	4.25		8.49		12.74	

So, when the actual number of loops are 2 and 3, and the thermal storage hours are 6, the winter months are still not fully covered as seen in the following heat maps:

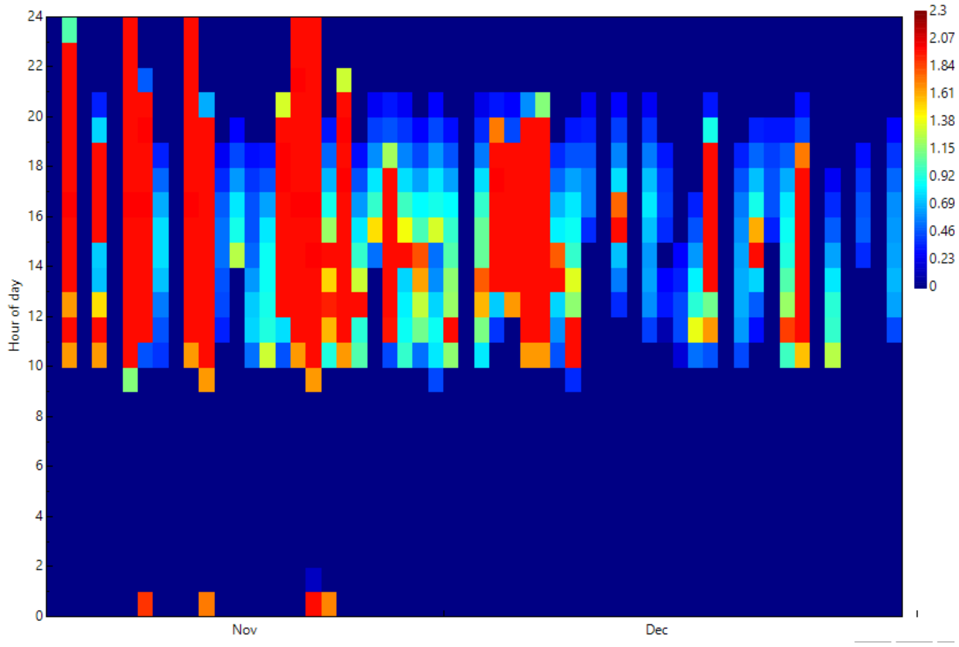


Figure 41: Heat map of Heat sink thermal power during winter months when the number of loops is 2 and the hours of storage are 6

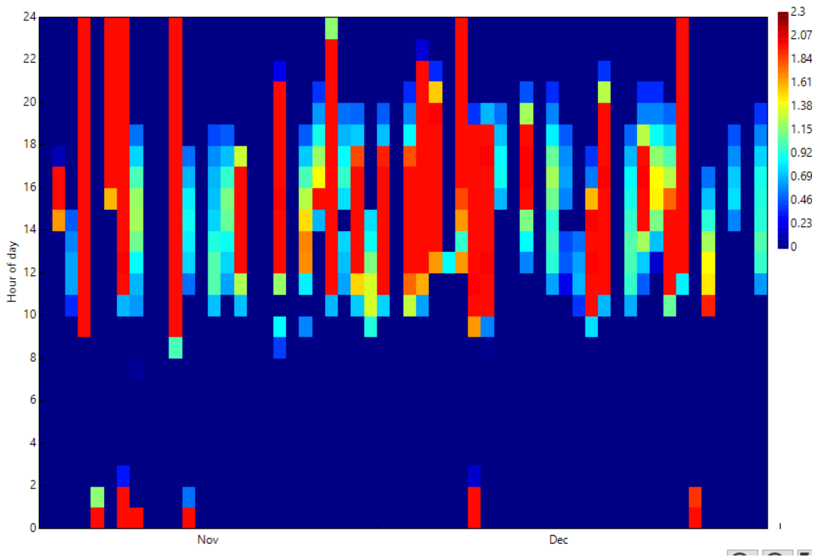


Figure 42: Heat map of Heat sink thermal power during winter months when the number of loops is 3 and the hours of storage are 6

So, the solar multiple is going to remain equal to 4.3.

When the thermal storage is the parameter, the expected is an increase in capacity factor and decrease of LCOH. Unfortunately, with 8h of thermal storage, the winter months are still not covered. What is increased though is the hours of some days and nights that the heat is produced. The Heat sink thermal power is covered throughout the whole summer and for more hours a day for the rest of the months, as seen in the following heat map:

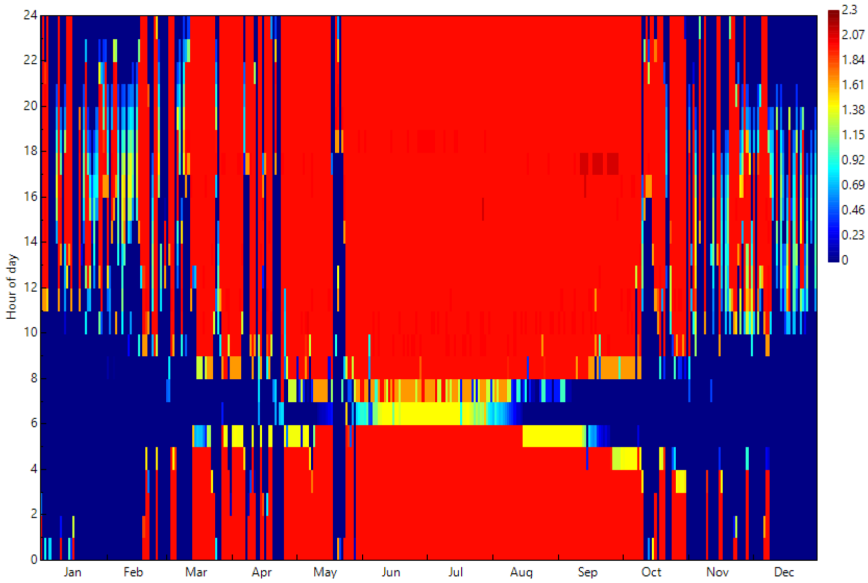


Figure 43: Heat map of Heat sink thermal power after Solar Multiple and Thermal Storage optimization

The thermal storage hours will remain equal to 6h. The capacity of the facility must be oversized, so that the thermal deficit in the thermal fluid also works as a thermal storage means [84]. So, the Heat sink value increases to 3.2MW as the number of loops are kept in 3 (solar multiple is 3.8), so that both summer and winter need are covered. As for the receiver parameter, the aim is to decrease the heat losses of it. The following table congregates all the results for every receiver:

Table 32: Results of simulation when the optimization is done according to different receiver.

Receiver	**Schott PTR80**	**Siemens UVAC 2010**	**Royal Tech CSP RTUVR 70M4**	**TRX70-125**
Metric	**Value**			
Annual Gross Thermal Energy Production w/ avail derate (kWt-hr)	10,914,515	11,127,236	11,202,910	11,148,049
Annual Net Thermal Energy Production w/ avail derate (kWt-hr)	14,784,966	15,064,119	15,144,739	15,076,426
Annual thermal freeze protection required (kWt-hr)	3,870,450	3,936,882	3,941,829	3,928,377
Capacity factor (%)	38.9	39.7	40.0	39.8
Annual electricity load (year 1) (kWe-hr)	3,753,440	3,824,540	3,828,714	3,816,120
Levelized cost of energy (c$/kWh)	2.39	2.39	2.37	2.38

The “Royal Tech CSP RTUVR 70M” receiver is the more efficient and is the final choice. The final monthly profile depicts the distributed daily capacity, in heat sink thermal power (MWt) of the solar thermal facility. December is not covered completely:

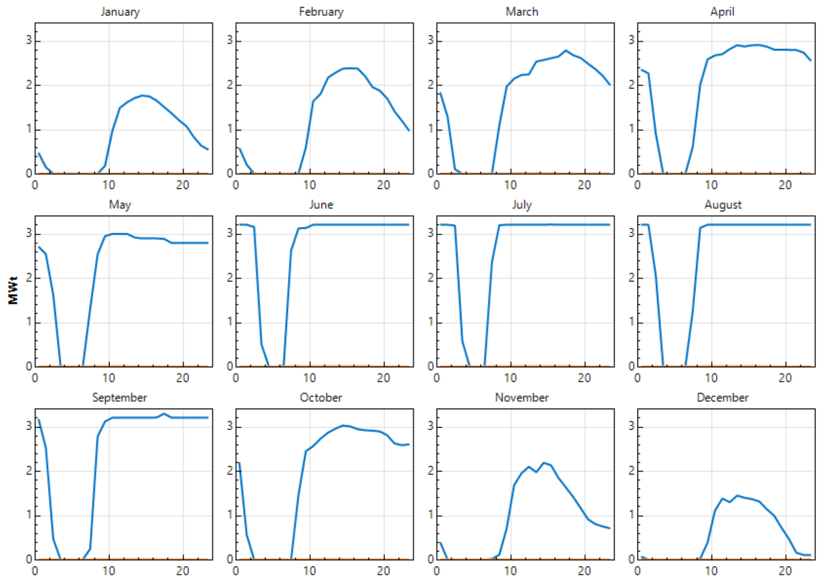


Figure 44: Monthly profile of the Solar Thermal facility Heat Sink thermal power outcome

The Heat Transfer fluid is the last measure of optimization. The heat exchange between the HTF and Steam in a steam generator and preheater, should be more efficient. The Heat transfer fluid is changed into Pressurized water. The Minimum and Maximum operating Temperatures of it are completely different than Therminol, due to its characteristics. The cost is also reduced since the thermal storage is going to be made of concrete. The Solar thermal field is heating the water from 75°C, 60bar to 210 °C, 55bar. There is heat exchange with the steam, that enters the LT-MED facility at 75°C, 0.4bar. This HTF is heating the thermal storage system, two concrete storages, one hot and one cold [79]. So, Loop inlet and outlet temperatures are equal to 75°C and 200°C, and thermal storage temperatures are also changed into these values. Freeze temperature is set at 30°C. In the financial parameters the Capital Cost is reduced by 7% (390,260$) since this system is cheaper [53],[88],[79]. The final result is the most efficient.

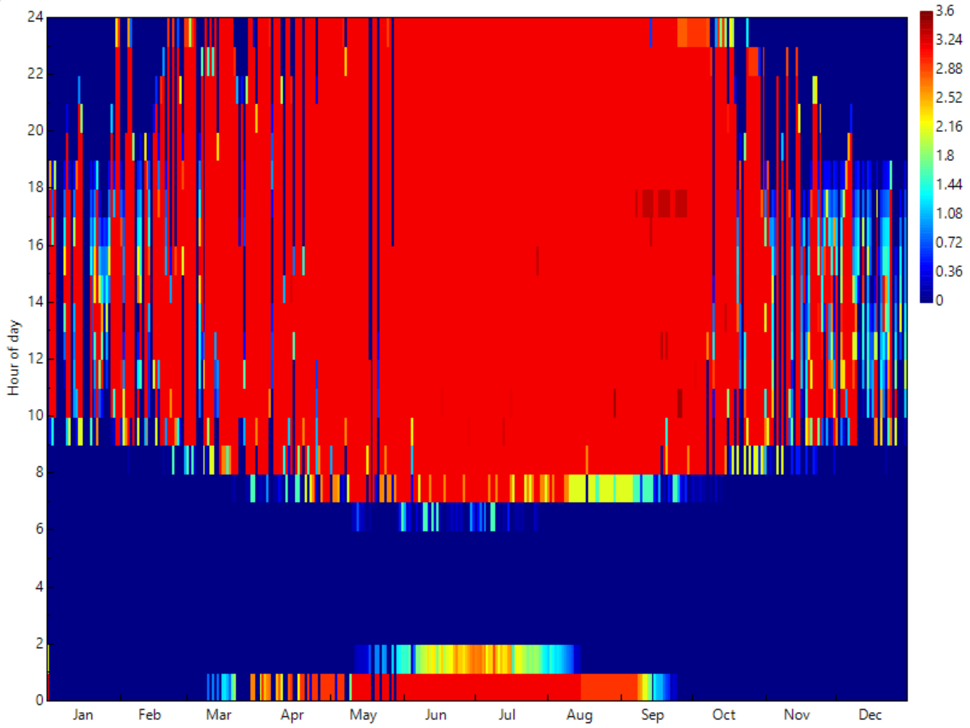


Figure 45: Heat map of Heat sink thermal power after optimization is complete

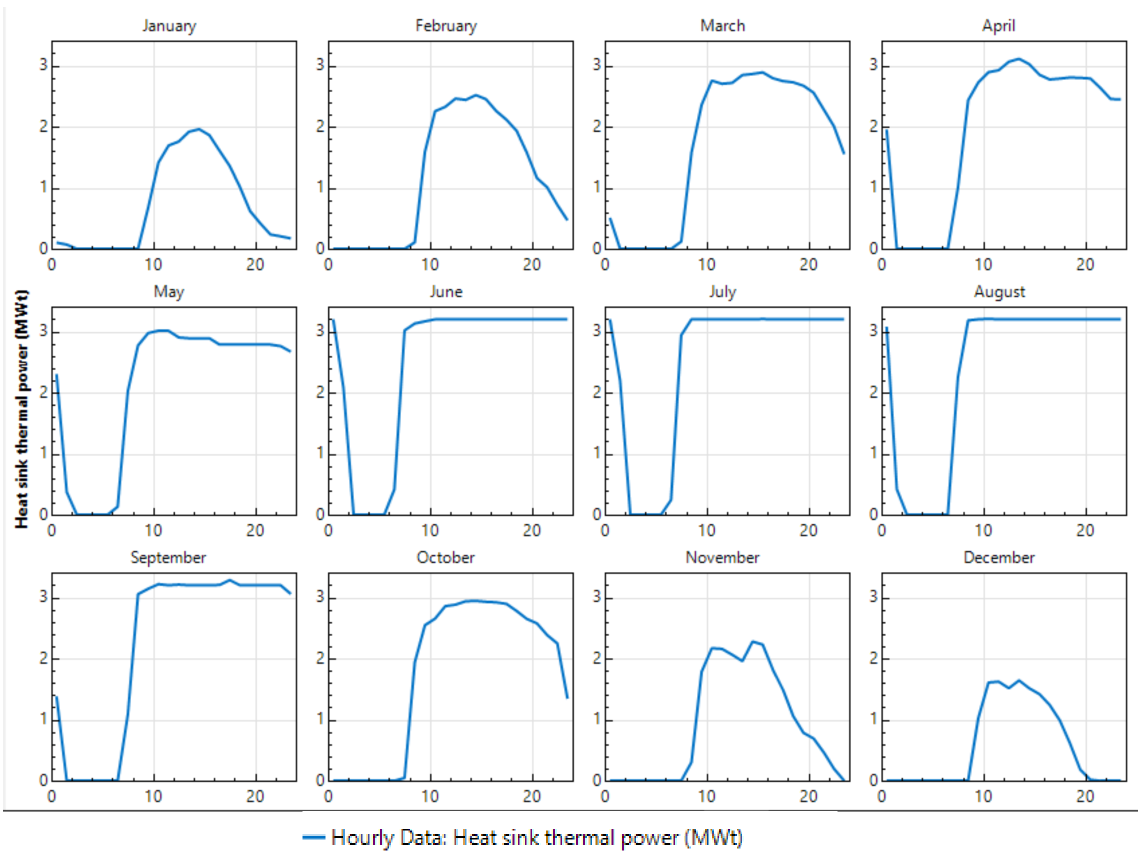


Figure 46: Monthly Profile of Heat sink thermal power CSP Parabolic trough optimized facility

Both January and February are thermally covered since the average daily capacity is really close to 1.92MW for both months.

Table 33: Summary of results of final solar thermal CSP IPH parabolic trough facility

Metric	Value
Annual net energy (year 1) kWh-t	14,122,566
Annual gross energy (year 1) kWh-t	14,308,892
Annual thermal freeze protection (year 1) kWh-t	186,325
Capacity factor%	50.4
Annual electricity load (year 1) kWh-e	217,081
Levelized cost of heat ¢/kWh-t	0.90

The capacity factor 50.4% is an excellent result, indicating that the plant is very efficient. The Levelized cost of heat is at its lowest, but the economic analysis is preliminary and will need improvement.

There is the possibility that when the parabolic troughs have an orientation with its long axis along east to west instead of north-south, their efficiency in the winter is better [89]. So, there is one effort of orienting this system by setting the collector azimuth at 90^{o}. The profile and summary in this case are the following:

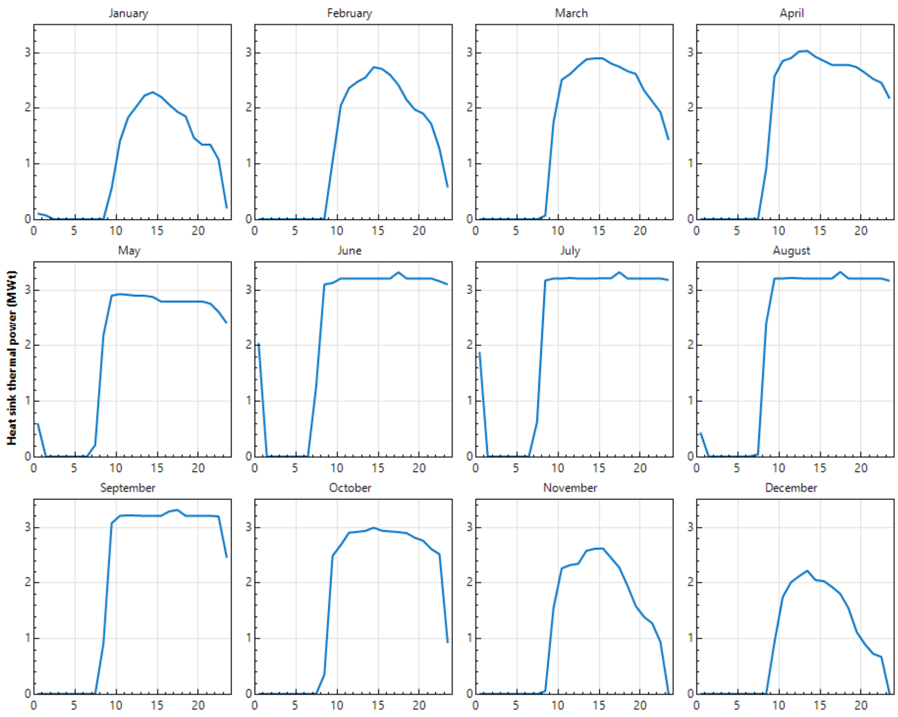


Figure 47: Monthly Profile of Heat sink thermal power CSP Parabolic trough optimized facility oriented east to west

Table 34: Summary of results of final solar thermal CSP IPH parabolic trough facility oriented east to west

Metric	**Value**
Annual net energy (year 1) kWh-t	13,744,610
Annual gross energy (year 1) kWh-t	13,902,425
Annual thermal freeze protection (year 1) kWh-t	157,815
Capacity factor%	49
Annual electricity load (year 1) kWh-e	190,875
Levelized cost of heat ¢/kWh-t	0.90

The final facility leads to very satisfactory results despite its orientation.

5 Final facility and location

This paragraph presents the characteristics of the final Solar Thermal Unit combined with the Multi-Effect Desalination facility. Both facilities are also located on the island.

The Concentrated Solar Thermal Facility is the Parabolic trough that uses as a Heat Transfer Fluid, Pressurized water. The following table summarizes the specifications of the CSP Parabolic Trough facility with thermal storage:

Table 35: Summary of Specifications of final CSP Parabolic trough facility

Parameter	**Value**
Solar Field	
Actual Field Thermal Output (MWt)	12.95
Target Solar Multiple	3.8
Hours of storage at design point (h)	6
Total Aperture reflective area (m^2)	19,620
Actual number of loops	3
Heat Transfer Fluid	
Type	Pressurized Water
Loop inlet HTF temperature (^oC)	75
Loop inlet HTF Pressure (bar)	60
Loop outlet HTF temperature (^oC)	200
Loop outlet HTF Pressure (bar)	55
Freeze Protection Temperature (^oC)	30
Collector Type	Eurotrough ET150
Number of modules per assembly	12
Aperture width total structure (m)	5.75
Length of Collector assembly (m)	150
Receiver Type	Royal Tech CSP RTUVR 70M4
Heat loss at design (W/m)	190.86
Optical Derate	0.862
Thermal Storage Tank	
Type	Concrete block with high and low temperature section
Cold tank heater temperature (^oC)	75
Hot tank heater temperature (^oC)	200
Tank heater efficiency	0.95
Thermal capacity (MWh-t)	19.2
Tank volume (m^3)	151
HTF volume (m^3)	141

The land area of the solar field equals 14acres or 14acres*0.00405km^2/acre=0.056km^2. Both units occupy a total land area of 0.0046 (desalination)+0.056(solar thermal)=0.061km^2 along with needed buildings for staff. The desalination unit will be near the sea, followed by the solar thermal field, and the complete unit should be in a non-inhabited area and plain landscape. The northern part of the island seems to fit the description as seen in the following figure:

Picture 9: Location of the LT-MED Concentrated Solar thermal facility on Lipsi island [90]

The Solar thermal facility, as described many times, consists of three loops. Each loop consists of eight collectors, and each collector SCA is a combination of twelve modules SCMs. The distance between collectors in parallel is 15m. The complete on location display is depicted as follows:

Picture 10: On location CSP Solar thermal facility[90]

In the selected location of the complete facility, there is the least disturbance of the natural environment, as the main flora of the island is in the southern central part. There is only one tourist beach in 350m away from the solar facility but far enough from the desalination facility and from where the seawater is pumped.

6 Discussion

This chapter aims to analyze the strengths and weaknesses of the work done. Also, to emphasize the competition with other technologies. Worldwide similar successful pilot plant examples are made. Both desalination and concentrated solar thermal power are technologies that should diminish environmental issues caused, as they are dependent on European and Local legislation.

It is a fact that water scarcity will deteriorate in the next years both worldwide and locally. Specifically, the Greek arid islands, keep on burdening the Hellenic State economy due to the water transportation from the mainland. Seawater desalination is one solution to the problem. The solution provided in the previous paragraphs has considerable potential. It utilizes the two most tested, reliable technologies: Multi-Effect Distillation Desalination and Concentrated Solar Power Parabolic troughs to provide the necessary thermal energy. The preliminary economic evaluation indicates that it is a feasible project. Still if there will be a possibility of realization, further analysis will be done by experts. The present facility does not produce electric power. At this scale it is not necessary. The desalination facility thermal needs are prioritized, and they are covered. Still, since the final goal is fossil fuel independence, there should be a simultaneous use of the CSP unit towards electric energy production, even though there is an existing network of renewable energy facilities on the larger Greek islands. The proposed unit is in the category of Industrial process heat with capacities smaller than 10MW. One of the worldwide facilities of a similar type is the Panoche Desalination Plant in California’s Central Valley, built and operated by WaterFX since 2013. It is a pilot plant of 0.4MWt, installed collector area of 656m^2, and Therminol XP as HTF. The brackish MED facility consists of 3-effects and produces 53m^3/day [85]. It is a successful pilot plant that led to planning a 24MWt similar facility [91]. Another facility is a 0.5MWt thermal and 35kWe power pilot plant in Louisiana [76]. This kind of facilities are blooming worldwide. They have a scope, including Desalination, such as Food processing, Dairy products, Pharmaceutical Processing, and Metals Industry and products [85]. Greece is without a doubt among the countries with potential for such kind of application since the Direct Normal Irradiance is generally high. It is undeniably a sound, valid, diversified suggestion compared to the competition. That is Reverse Osmosis combined with other renewable energies such as Wind or Photovoltaics. With an aiming lifetime of 30 years, it is providing thermal energy throughout the whole year with less use of the back-up fossil fuel system and without intermittencies. What lucks is the further technical analysis and optimization of both the Desalination Facility and Solar Thermal one, because there is a focus on the result. A continuation of the present work should focus on the combination of electric power production with the implementation of Rankine cycle, and a detailed design of the desalination facility, where it will be known how many effects are needed, as well as other valuable details.

The European and Local Legislation should be advised, to locate the facilities properly. The effects of brine or other chemicals' disposal to the natural environment are critical and the subject of research. Seawater intake, discharge of brine containing additives, brine physical properties, antiscalants, antifoaming agents, corrosion inhibitors, and products are all these environmental factors that require special attention [53]. Environmental awareness is a delicate matter because the Greek islands and surrounding ecosystems are of exceptional beauty and unique in the world. Fossil fuel dependency is not connected with environmental pollution and is one of the causes of climate change. Concentrated solar thermal parabolic troughs are not necessarily burdening the local environment. There should be though careful maintenance of the land they will be installed. For example vegetation should be absent due to high temperatures of the heat transfer fluid, so the possibility of grass fires should be zero [53].

7 Conclusions

Aiming to respond to the freshwater requirements of the Greek arid island of Lipsi, in Dodecanese complex, a design and simulation of a concentrated solar thermal power plant took place, to be combined with a Multi-Effect distillation desalination facility. The specific technological proposal resulted after an extended analysis of both from an economic and technical perspective. The simulation program is the System Advisor Model, and the performance result is worthwhile since the capacity factor is high, and the Levelized cost is low. The following are the major conclusions of this study:

- The literature review and problem stating, provide all the necessary information for the desalination technologies, and renewable energy sources, that conclude to the justified proposal and choice of these, as one solution to the problem.
- The aspects of the desalination and concentrated solar technology are chosen accordingly to the Greek island climatic conditions. Such a combination can easily be incorporated in other islands as well.
- The proposed design resulted in satisfying thermal performance covering the specific need and can be altered for any given location to forecast the solar thermal potential at such small or broad scale.
- It is quite a novelty for Greece to develop and exploit the potential of concentrated solar thermal technology, with its favorable extraordinary solar resource and high level of direct normal irradiation. The country can differentiate from the usual wind and photovoltaics energy sources.
- However, the case requires additional research investigation for the system design parameters such as solar field configuration, collector and receiver choice, heat transfer fluid, thermal storage.
- The optimum condition for the technical and economic viability of concentrated solar power along with desalination requires extended studies and sensitivity analysis.

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Appendix

Eurotrough Collectors[92]

"Eurotrough collector, used at the Plataforma Solar, is tracking the sun from sunrise to sunset. The sun's radiation concentrates with the parabolic mirror facets on the absorber tube along their focal line. The heat transfer fluid circulates through the absorber tube [92]."

Identical 12 m long collector modules are combined to consist the collector assembly. Each module comprises of 28 parabolic mirror panels (7 along the horizontal axis between pylons and 4 in a vertical cross-section). Each mirror is supported on the structure at four points on its backside. This permits the glass to bend within the range of its flexibility without effect on the focal point. The 150 m long ET150 has 12 collector modules and an aperture area of 817.5 m² [92].

"A supporting construction with torque-box design has been selected for the EuroTrough, with less weight and less deformations of the collector structure due to dead weight and wind loading than the reference designs (LS-2 torque tube or the LS-3 V-truss design, both commercial in the Californian plants). This reduces torsion and bending of the structure during operation and results in increased optical performance and wind resistance. The weight of the steel structure has been reduced about 14% as compared to the available design of the LS-3 collector. The central element of the box design is a 12-m long steel space-frame structure having a squared cross section that holds the support arms for the parabolic mirror facets. The torque box is built out of only 4 different steel parts. This leads to easy manufacturing and decreases required efforts and thus cost for assembling on site. Transportation volume has been optimized for maximum packing. The structural deformation of the new design is considerably less than in the previous design (LS-3), which results in a better performance of the collector. Thus, the spillage during operation can be reduced by approximately 2-10 percentage points [92]."

"The design utilizes mirror supports that make use of the glass facets as static structural elements, but at the same time reduce the forces on the glass sheets by a factor of three. This promises less glass breakage with the highest wind speeds. Absorber tube supports were designed such to reduce the breakage risk and to ease mirror cleaning in comparison to the LS-3 collector. The accuracy of the concentrator is achieved by a combination of prefabrication with jig mounting on site. The majority of the structural parts are produced with steel construction tolerances. The accuracy for the mirror supports is introduced with the glass brackets on each of the cantilever arms. This concept allows minimum assembly manpower and cost in series fabrication of solar fields [92]."

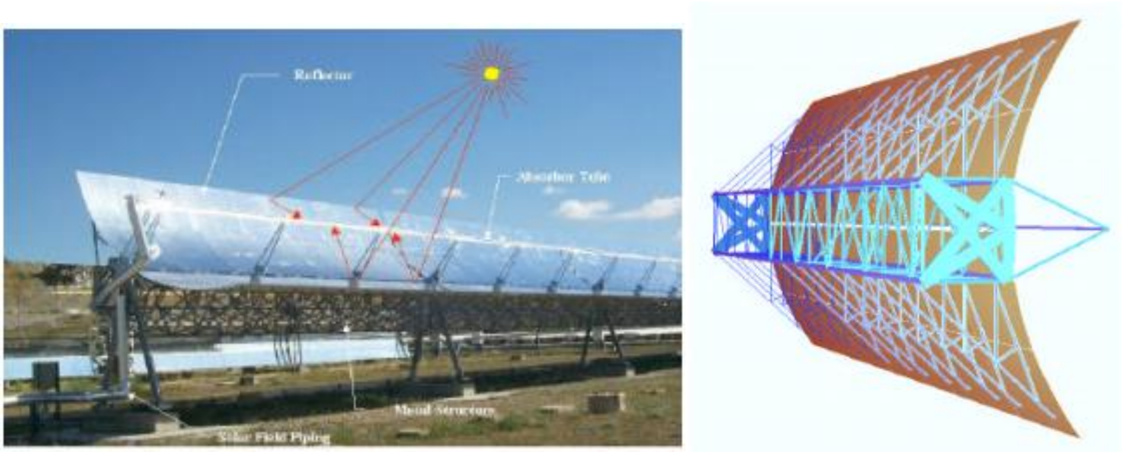

Figure 48: Working Principle of the EuroTrough collector and Computer Model of the EuroTrough Collector with Torque-Box Design [92]

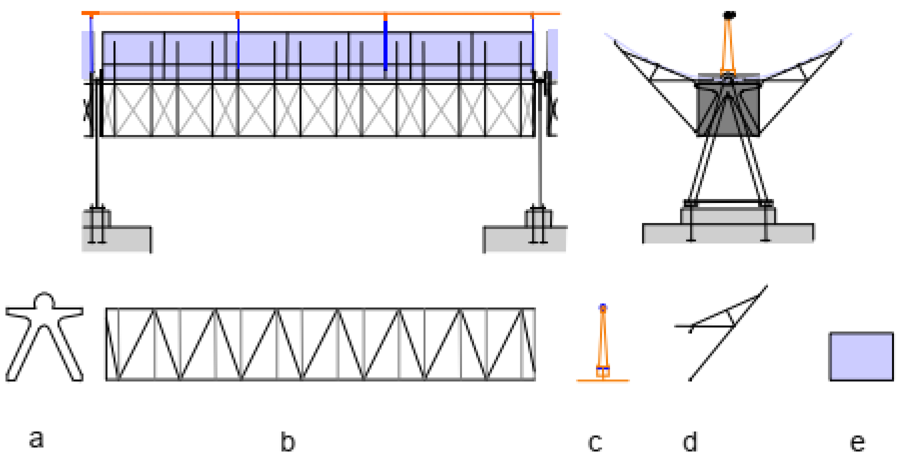

Figure 49: EuroTrough collector element consisting out of (a) 2 endplates; (b) 4 simple steel frames screwed to a torque box; (c) 3 absorber tube supports; (d) 28 cantilever arms and (e) 28 mirror facets [92]

Optical parameters of collectors and Total Weighted losses of receivers[69]

The optical calculations for the collectors are values that SAM calculates using the equations described below. These values cannot directly be edited [69]. Similarly, the total weighted losses are used to estimate the optical and thermal losses in the solar field at the design point. The active receiver, which is a weighting fraction of the four receiver variations, losses heat. The heat loss at design is used to calculate the design point total loop conversion efficiency and the solar field aperture area. The same occurs with the total optical losses or optical derate. All equations for collectors and receivers' calculations are in the following table:

Table 36: Equations used to calculate the optical efficiency of the collectors and total weighted losses of the receivers [69]

Variable Name	**Equation**	**Note**
	Collectors	
Length of single module	= *Length of Collector Assembly* ÷ *Number of Modules per Assembly*	L_{col} used in End Loss at Design described below.
Incidence angle modifier at summer solstice	$= IAM_0 + \sum_{i=1}^{N} IAM_i \frac{\theta^i}{\cos\theta}$	Not used in actual efficiency calculation. Provided as reference only. Theta is in radians.
End loss at summer solstice	$= 1 - L_{f,ave} * \tan(\theta) - \left(\frac{N_{SCA}}{2} - 1\right) * \frac{2 * EG}{N_{SCA} * L_{col}}$ where, $EG = L_{f,ave} * \tan(\theta) - L_{row\ spacing}$	Optical end loss at noon on the summer solstice due to reflected radiation spilling off, of the end of the collector assembly. This value is provided as a reference and is not used in determining the design of the solar field.
Optical efficiency at design	= *Tracking Error* × *Geometry Effects* × *Mirror Reflectance* × *Dirt on Mirror* × *General Optical Error*	The collector's optical efficiency under design conditions
	Receivers	
Heat loss at design	$= \sum_{i=1}^{4} f_{weight,i} * \dot{q}_{hl,i}$	$f_{weight,i}$ is the weighting fraction for each variation
Optical derate	$= \sum_{i=1}^{4} f_{weight,i} * \eta_{bellows,i} * \eta_{rec,dirt,i} * \eta_{absorb,i} * \tau_{env,i}$	$\tau_{env,i}$ is the envelope transmittance